

# **You had me at Habitable!**

## ***NASA's Search for Habitable Planets & Life Beyond the Solar System***

### ***Exoplanet Exploration Program***

**Dr. Gary Blackwood, Program Manager**

Jet Propulsion Laboratory

California Institute of Technology

**March 21, 2017**

**SETI Institute Weekly Colloquium**

Program Overview

Science Updates

How Do We Discover & Characterize Exoplanets?

Progress towards 2010 Decadal Survey Priorities

Plan Forward: Science and Technology

ExoComm: Show Me the Planets!

# Program Overview

## Science Updates

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# NASA Exoplanet Exploration Program

Astrophysics Division, NASA Science Mission Directorate

*NASA's search for habitable planets and life beyond our solar system*



Program purpose described in  
**2014 NASA Science Plan**

1. Discover planets around other stars
2. Characterize their properties
3. Identify candidates that could harbor life

ExEP serves the science community and NASA by implementing NASA's space science vision for exoplanets

# NASA Exoplanet Exploration Program

## Space Missions and Mission Studies

Kepler,  
K2

WFIRST

Starshade

Decadal Studies

Coronagraph

## Public Communications



## Supporting Research & Technology

### Key Sustaining Research



Large Binocular  
Telescope Interferometer

Keck Single Aperture  
Imaging and RV



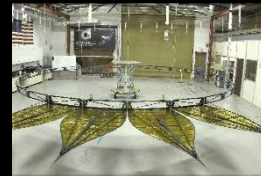
NN-EXPLORE

### Technology Development

Coronagraph  
Masks

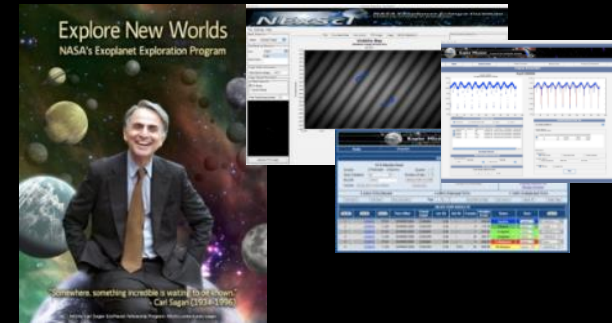


High-Contrast  
Imaging



Deployable  
Starshades

### NASA Exoplanet Science Institute

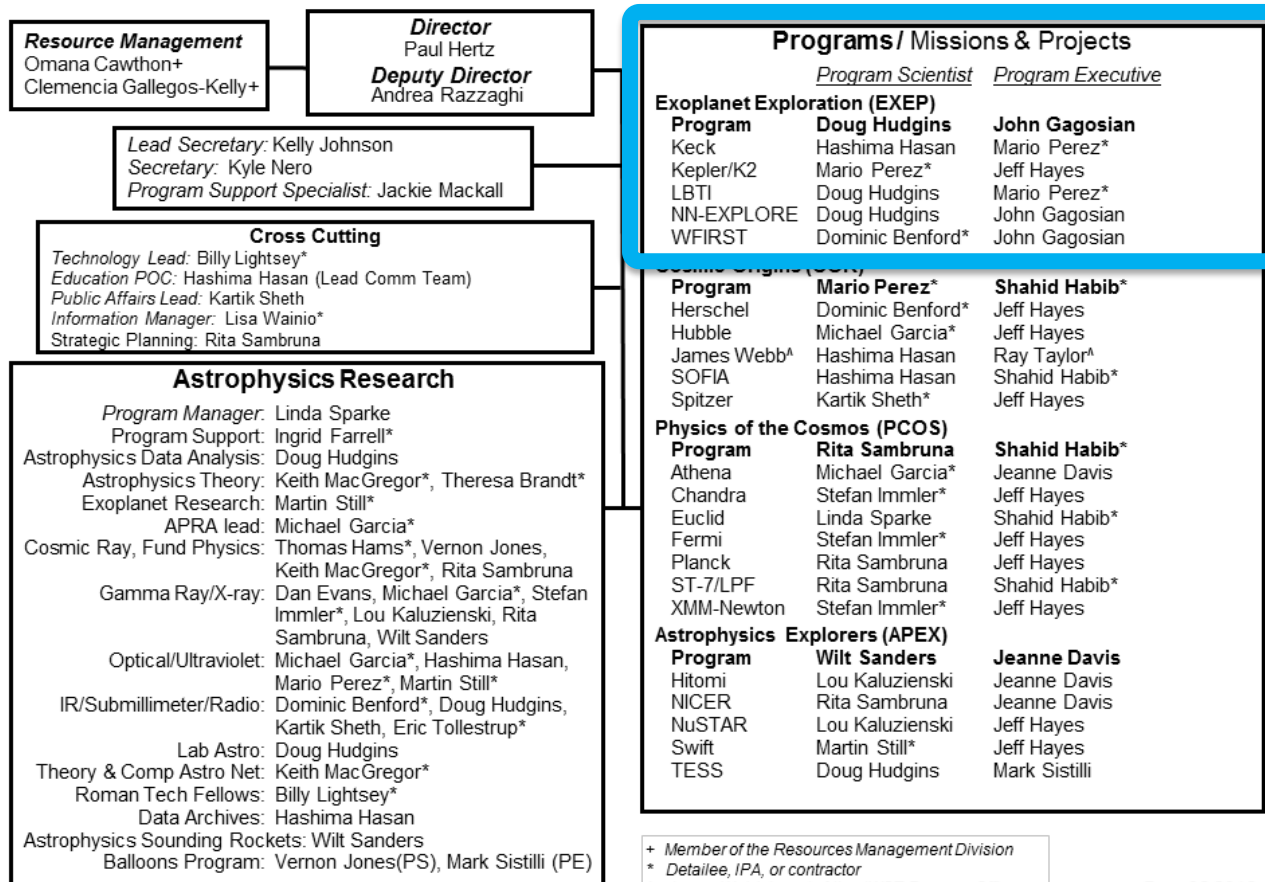


Archives, Tools, Sagan Fellowships,  
Professional Engagement

<https://exoplanets.nasa.gov>

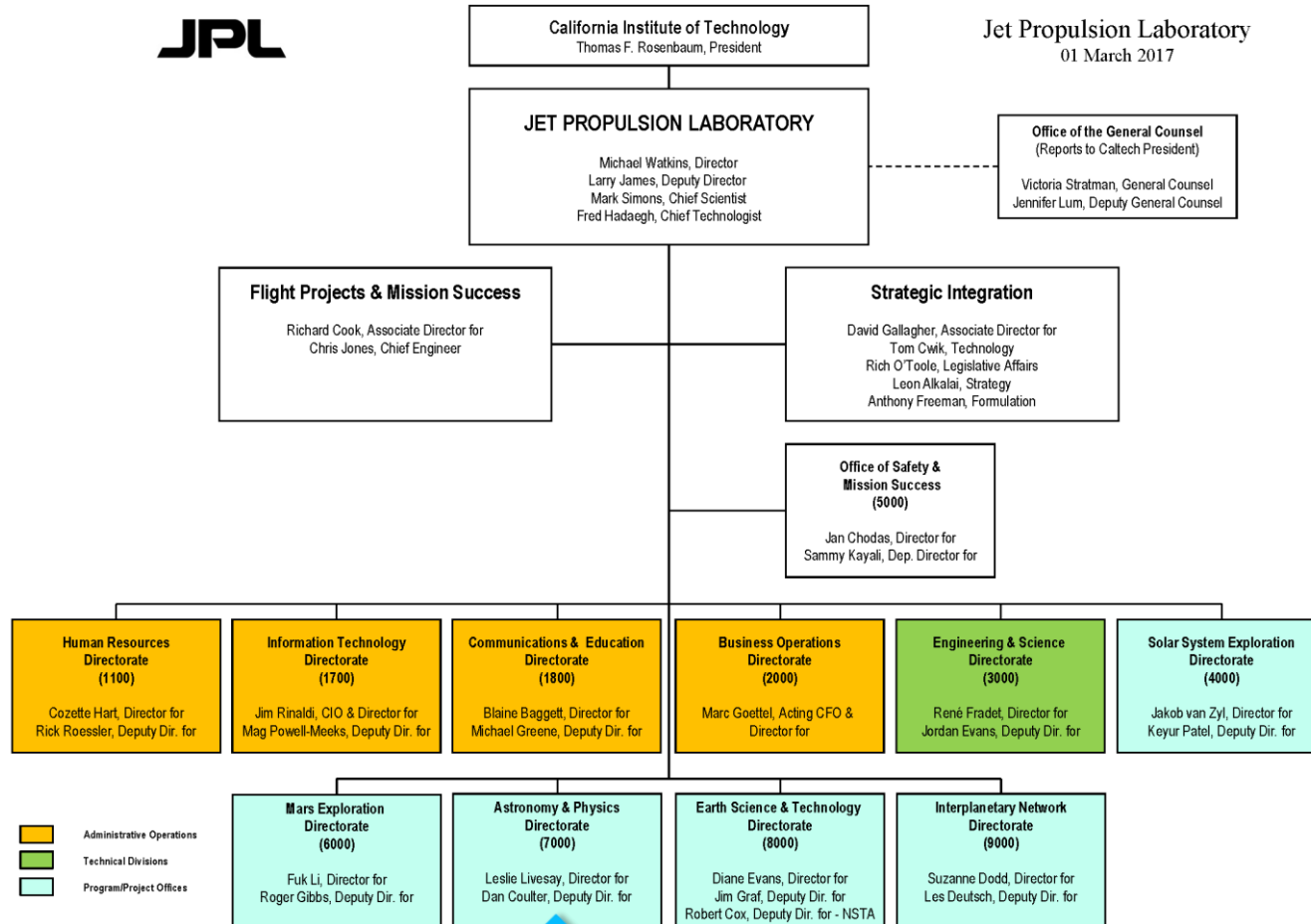
# ExEP is a Program Office within the NASA Astrophysics Division

## Astrophysics Division, NASA Science Mission Directorate



Dec, 06 2016

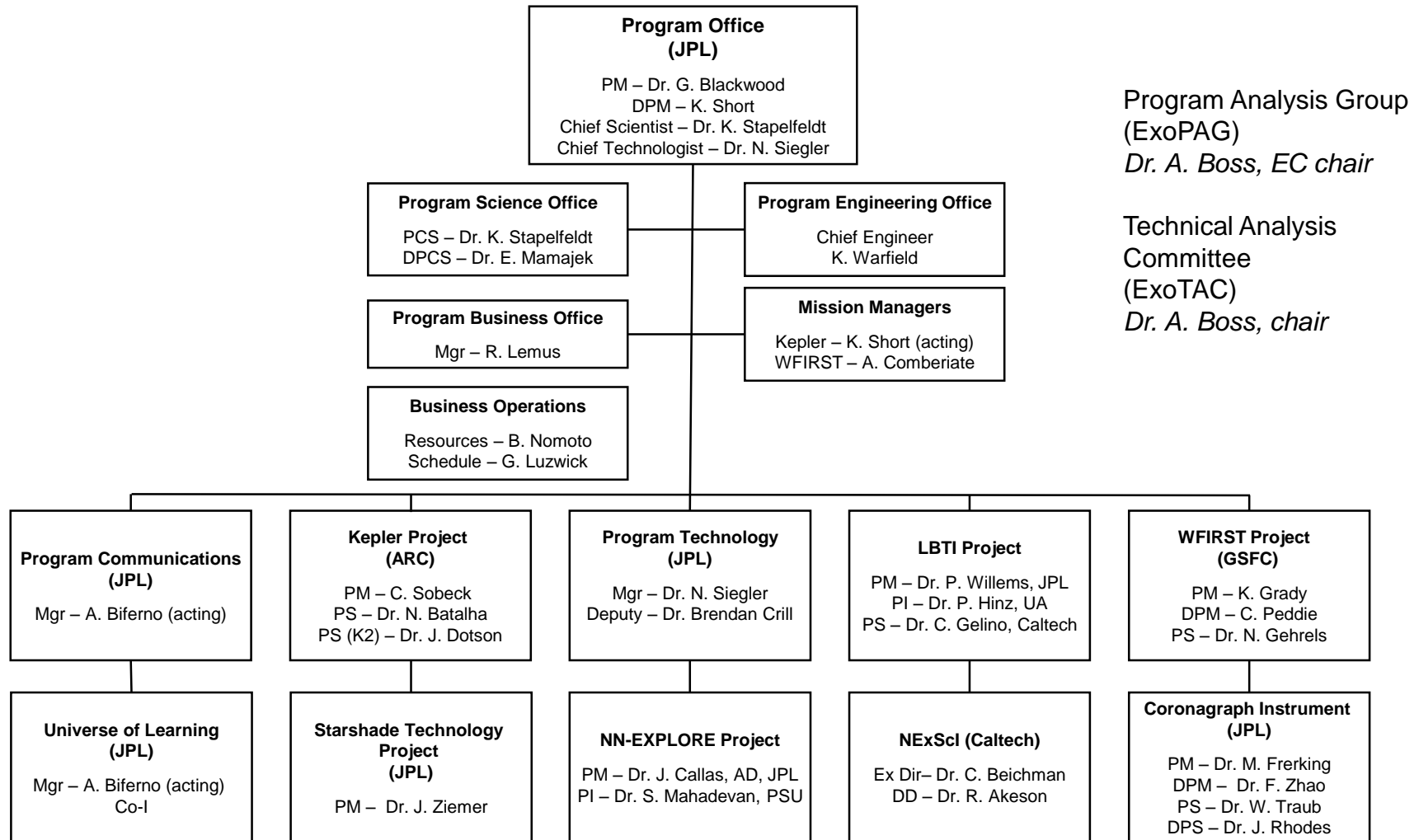
# ExEP Resides within NASA JPL Directorate



ExEP (office 730) within APST Directorate

# ExEP Resides within NASA JPL Directorate

Astrophysics Division, Science Mission Directorate



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## Science Updates

How Do We Discover & Characterize Exoplanets?

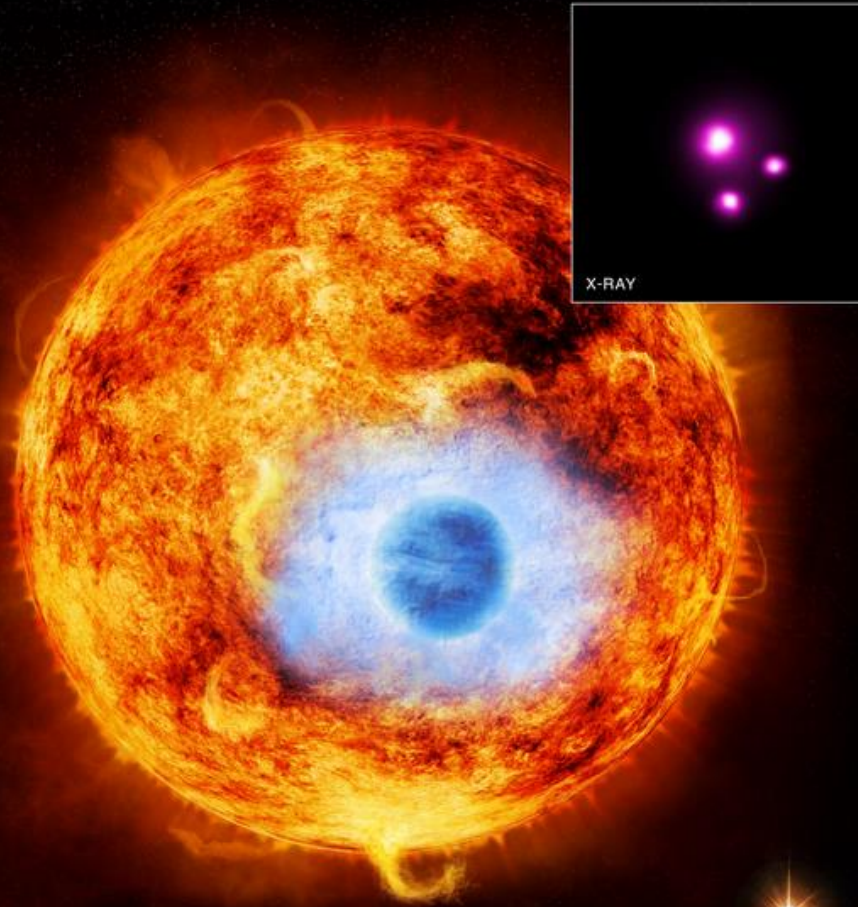
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# NASA's Chandra Sees Eclipsing Planet in X-rays for First Time

HD 189733b



*Credit:  
K. Poppenhaeger, 2013*

ILLUSTRATION

# Seven ExoPlanets Above the Fold

"All the News  
That's Fit to Print"

## The New York Times

Late Edition

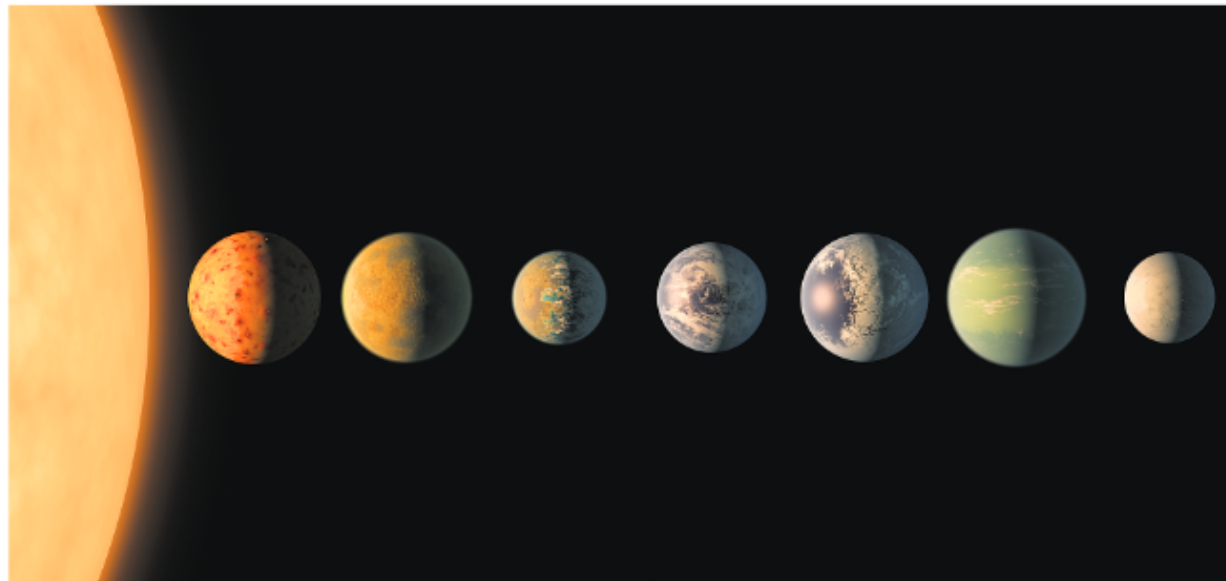
Today, patchy morning fog, partly sunny, warm, high 64. Tonight, mostly cloudy, mild, low 52. Tomorrow, clouds and sunshine, showers, high 66. Weather map is on Page B9.

VOL. CLXVI ... No. 57,517

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NEW YORK, THURSDAY, FEBRUARY 23, 2017

\$2.50



A rendering of newly discovered Earth-size planets orbiting a dwarf star named Trappist-1 about 40 light-years from Earth. Some of them could have surface water.

### Circling a Star Not Far Away, 7 Shots at Life

By KENNETH CHANG

### Uber's Culture Of Gutsiness Under Review

By MIKE ISAAC

### Migrants Hide, Fearing Capture on 'Any Corner'

By VIVIAN YEE

No going to church, no going to the store. No doctor's appointments for some, no school for others. No driving, period — not

**IMMIGRATION** A police department worries a crackdown will harm work to fight gangs. PAGE A11

**MEXICO** The secretary of state pays a visit at a time of rising

duras.

If deportation has always been a threat on paper for the 11 million people living in the country illegally, it rarely imperiled those who did not commit serious crimes. But with the Trump ad-

### TRUMP RESCINDS OBAMA DIRECTIVE ON BATHROOM USE

#### ENTERING CULTURE WARS

#### Question of Transgender Rights Splits DeVos and Sessions

This article is by Jeremy W. Peters, Jo Becker and Julie Hirschfeld Davis.

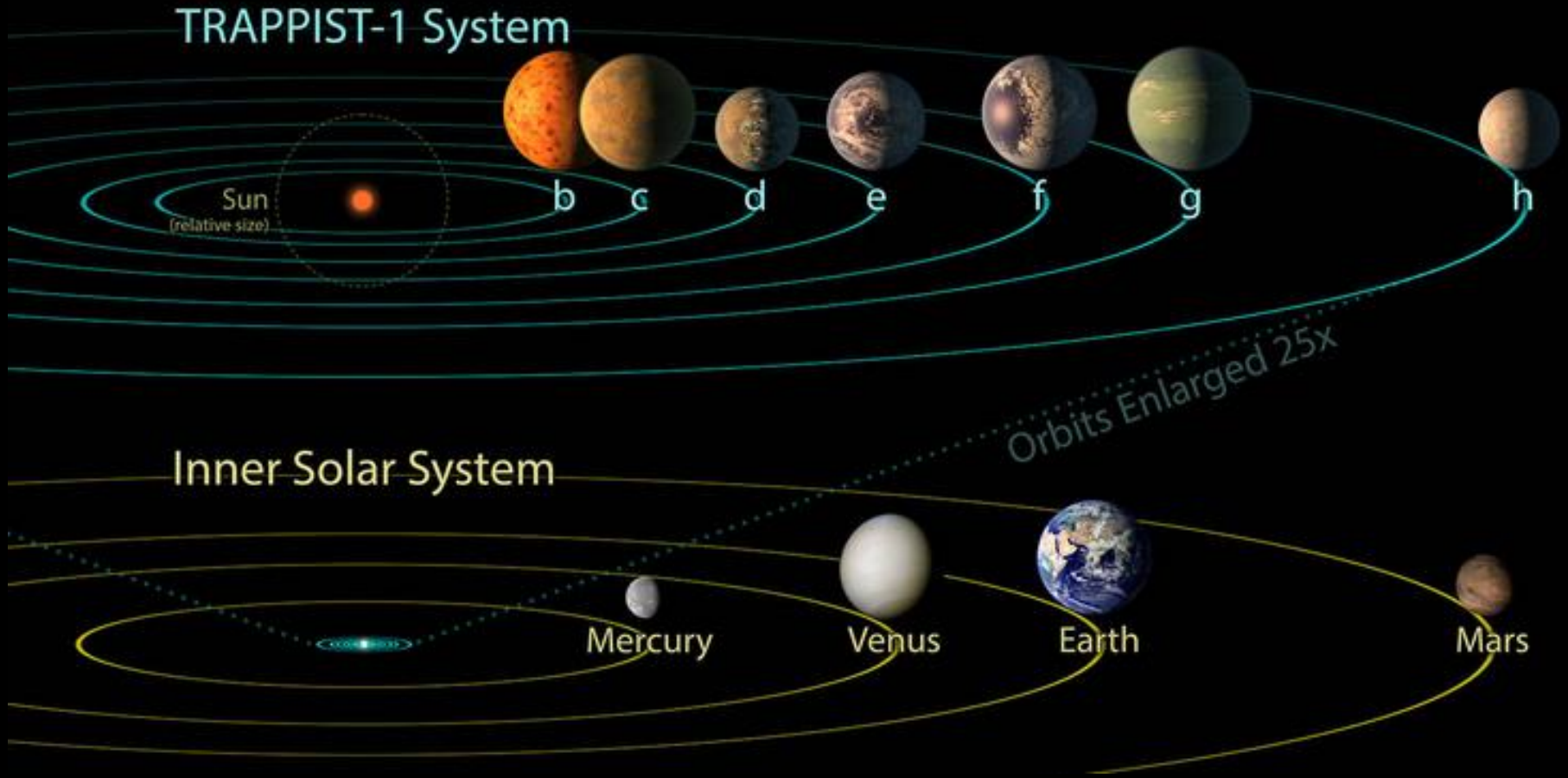
WASHINGTON — President Trump on Wednesday rescinded protections for transgender students that had allowed them to use bathrooms corresponding with their gender identity, overruling his own education secretary and placing his administration firmly in the middle of the culture wars that many Republicans have tried to leave behind.

In a joint letter, the top civil rights officials from the Justice Department and the Education Department rejected the Obama administration's position that nondiscrimination laws require schools to allow transgender students to use the bathrooms of their choice.

That directive, they said, was improperly and arbitrarily devised, "without due regard for the primary role of the states and local school districts in establishing

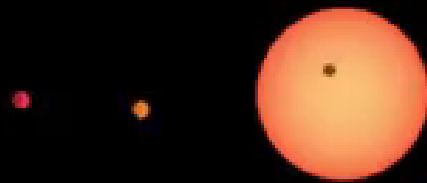
# Trappist-1 Discovery

The Richest Set of Earth-sized Planets Ever Found



*Credit: NASA/JPL*

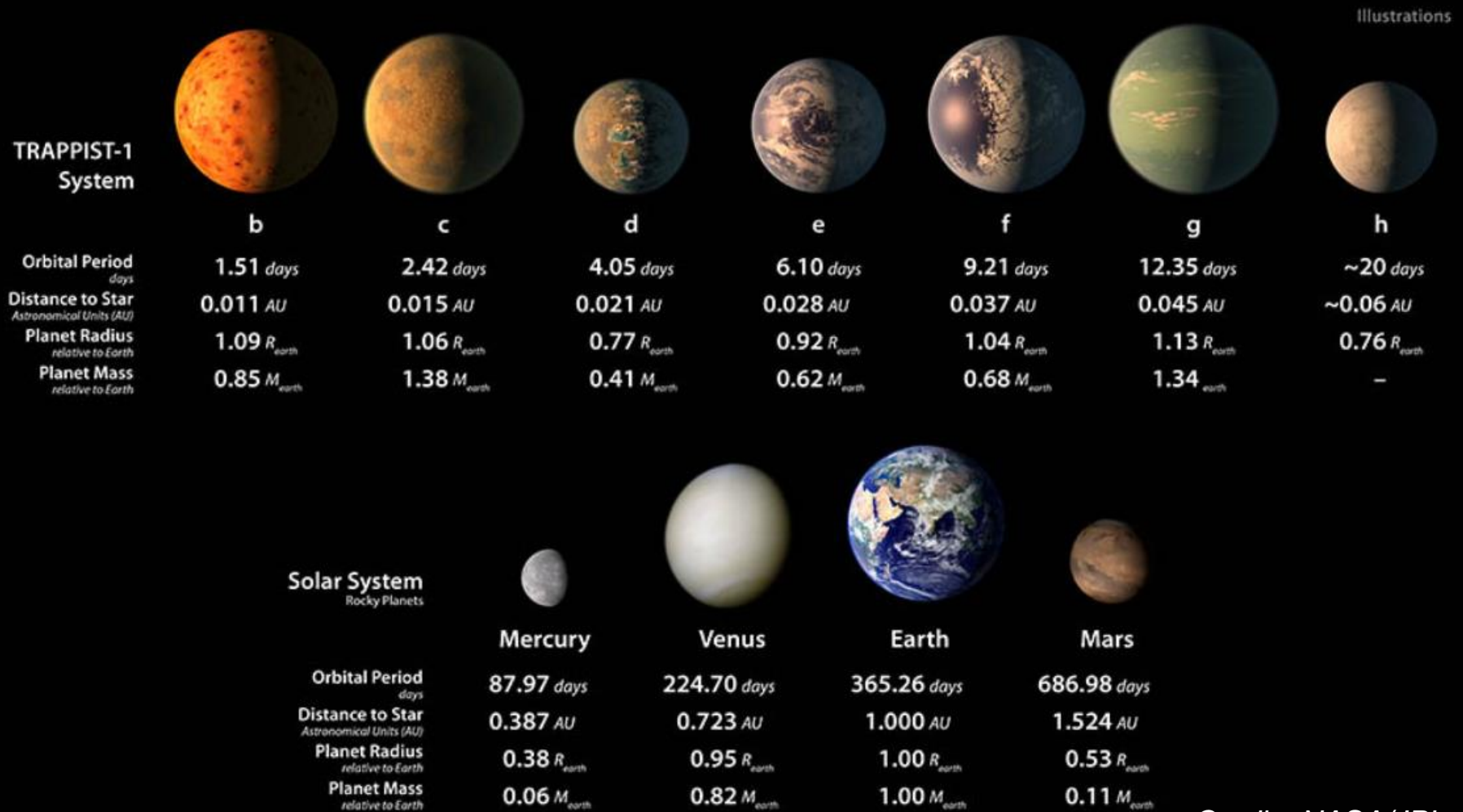
# How Spitzer Observed the Trappist-1 System



*Credit: NASA/JPL*

# Spitzer Measures Planet Size & Transit Timing

Orbital mechanics used to deduce mass from transit timing variations



Credit: NASA/JPL

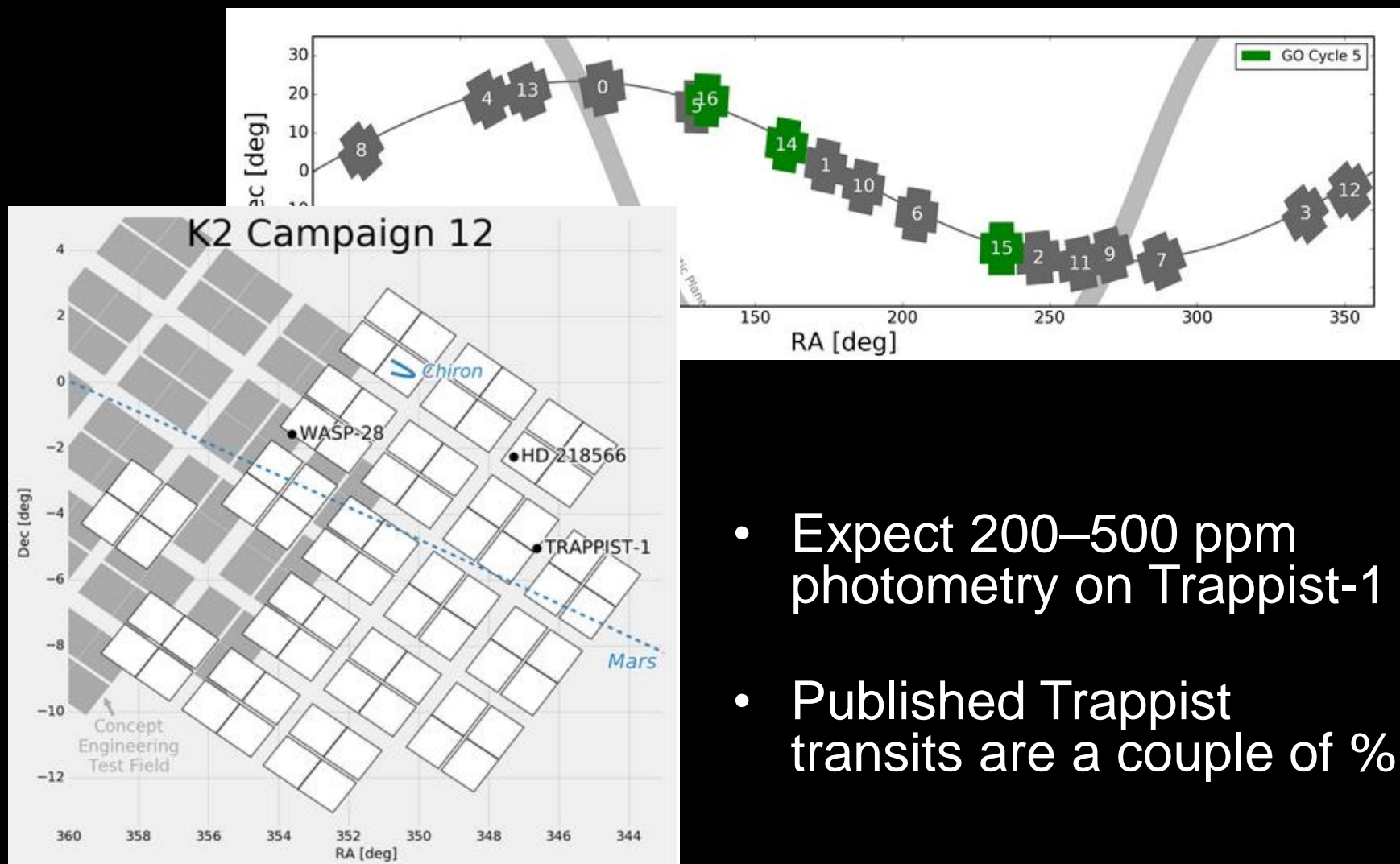
# Key Takeaways from Trappist Discovery



- This is the **richest set of Earth-sized exoplanets ever found** orbiting a single star, with 3 in the habitable zone. Liquid H<sub>2</sub>O possible.
- It shows that red dwarf stars, the most common type of star, can host rich planetary systems. **More discoveries like this can be expected**, such as from the 2018 NASA TESS Explorer mission
- The **Trappist exoplanets will be top targets for future observations** with the James Webb Space Telescope. The presence and composition of an atmosphere can be measured through infrared spectra taken during transit; but the observations will be difficult.
- Most exoplanets do not transit their star. For the general case, **direct imaging remains essential for measuring atmospheres and possible biosignatures.**

# K2 Campaign 12: 80 days on Trappist-1

Campaign ends March 4; raw data release mid-March

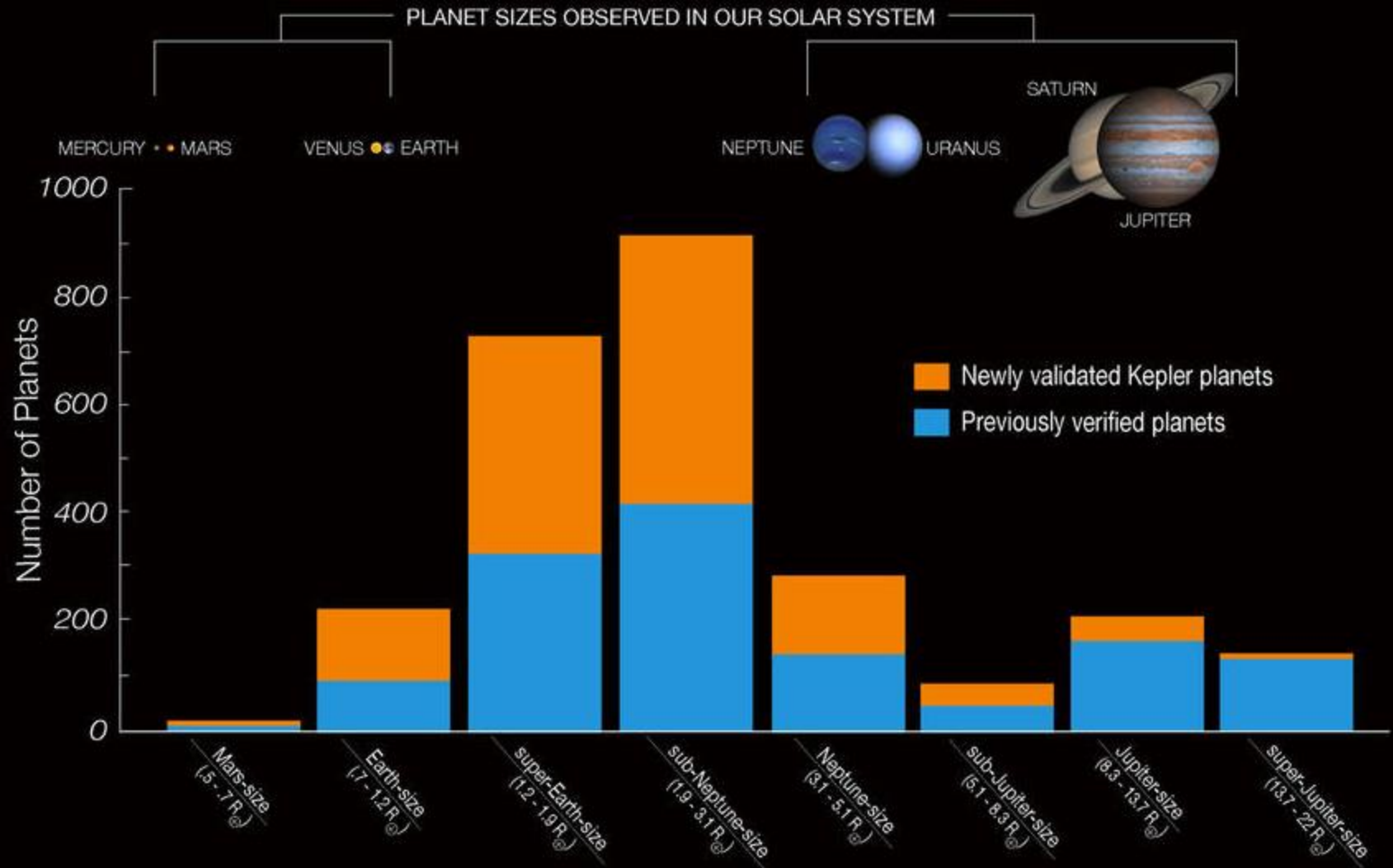


- Expect 200–500 ppm photometry on Trappist-1
- Published Trappist transits are a couple of %

# Kepler's Verified Planets, by Size

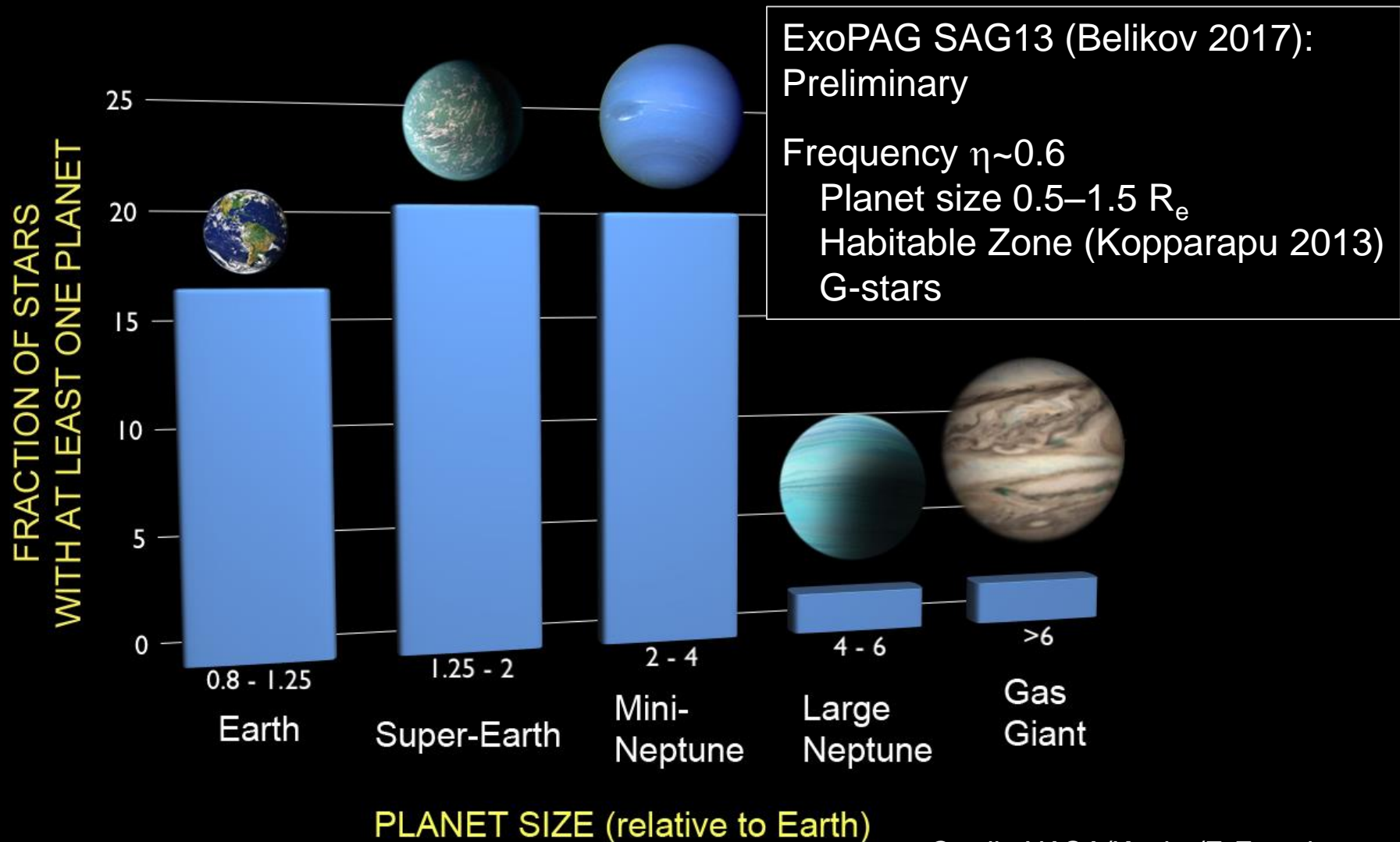
As of May 10, 2016

Final data release: spring 2017



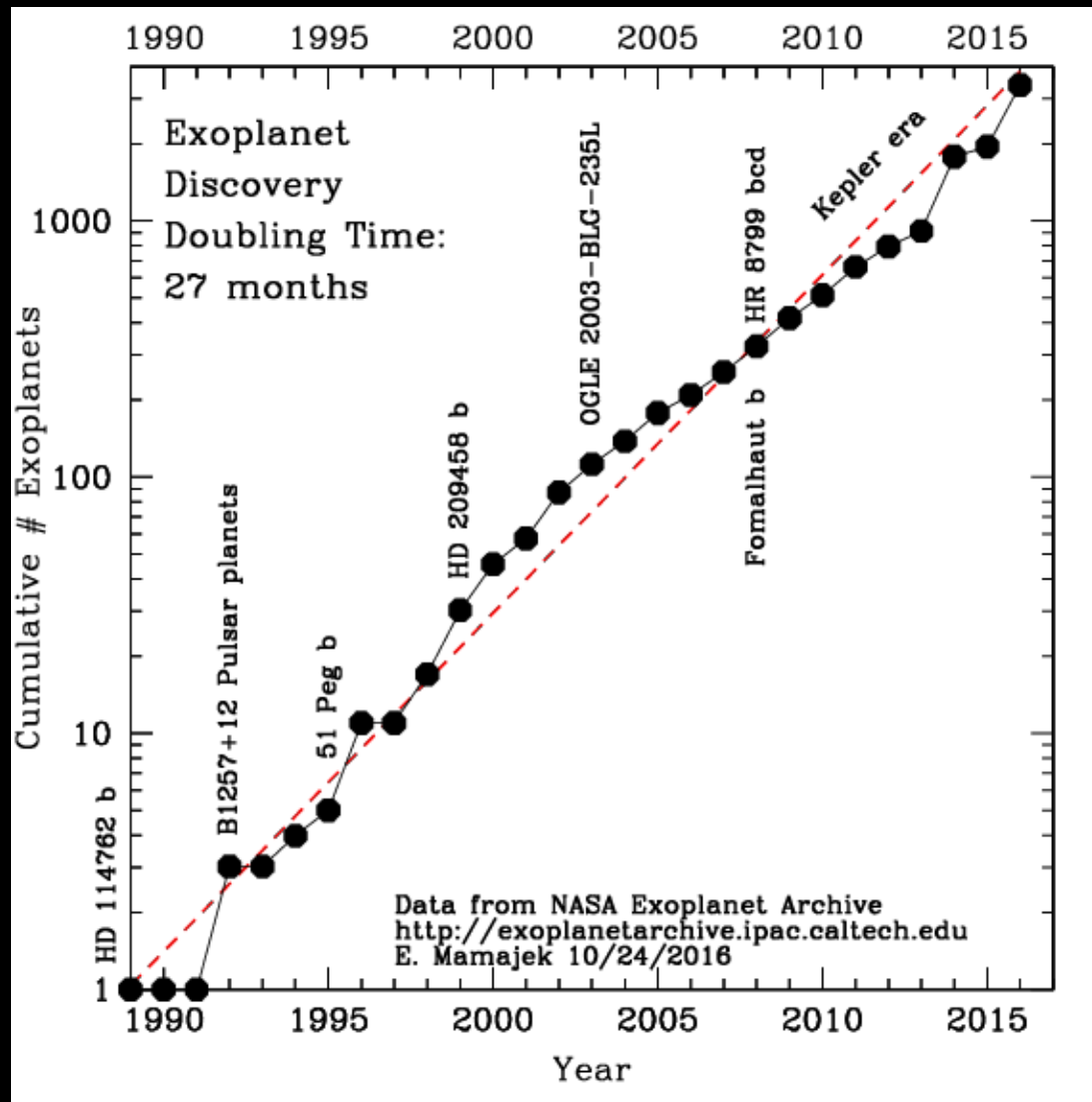
Credit: NASA/ARC

# Exoplanetary Occurrence Rates



Credit: NASA/Kepler/F. Fressin

# Exoplanet Discovery Doubling Time



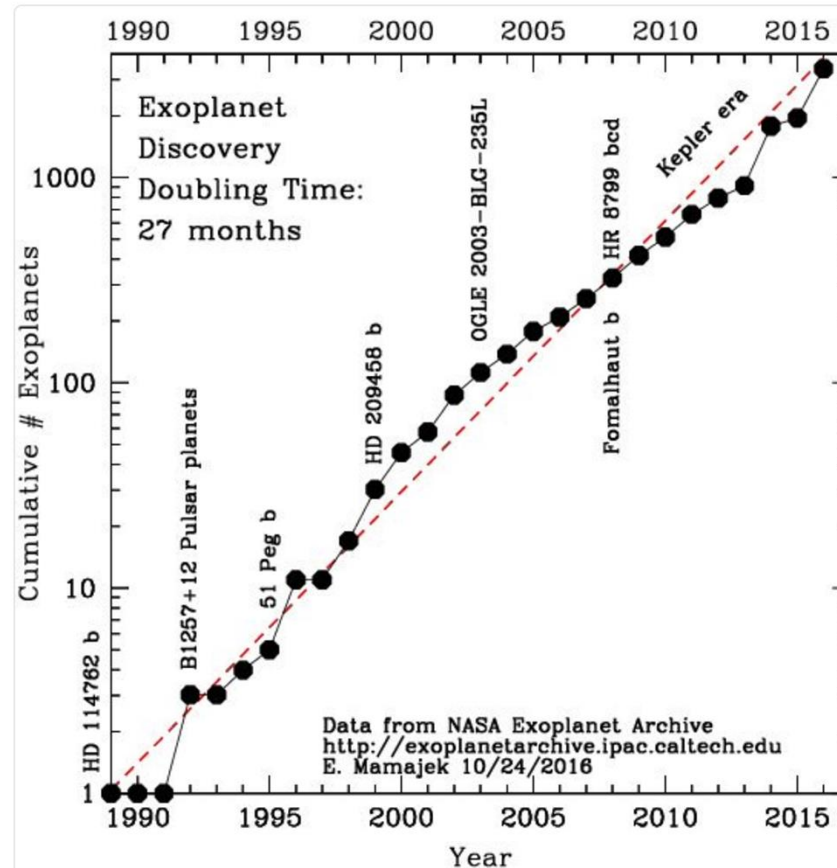
# “Mamajek’s Law”

NASAExoplanetArchive and 3 others liked



Eric Mamajek @EricMamajek · Oct 24

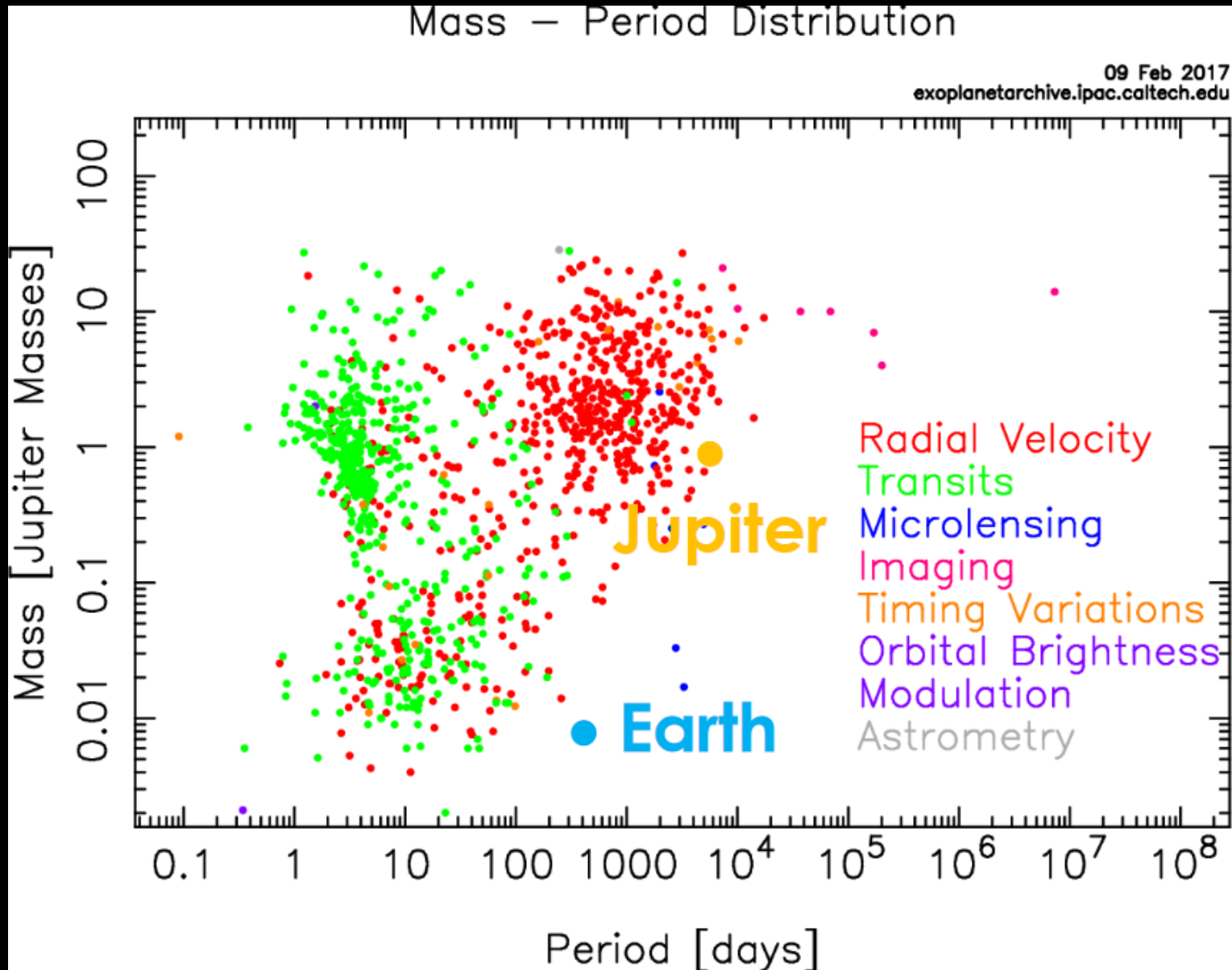
@aussiastronomer @NASAExoArchive Updtd versn of #exoplanet discovery #  
plot. Doubling time still ~27 months. Hit mil in 2034, bil in 2057?



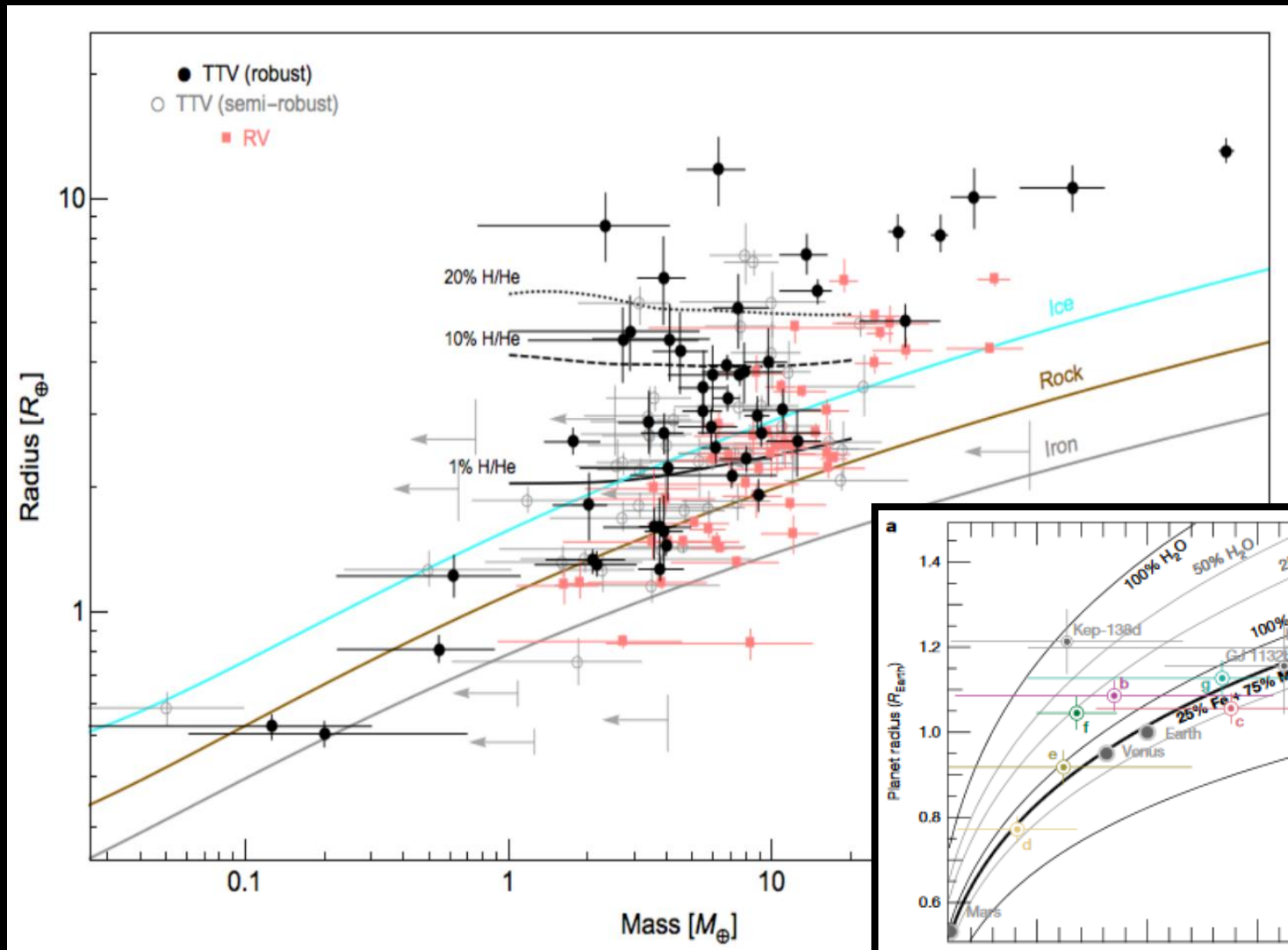
2 20 18

Credit: J. Christenson

# Exoplanet Mass – for a Subset of Discoveries



# Where are the Rocky Planets?



Credit: Hadden & Lithwick 2016

Credit: Gillon et al. 2017

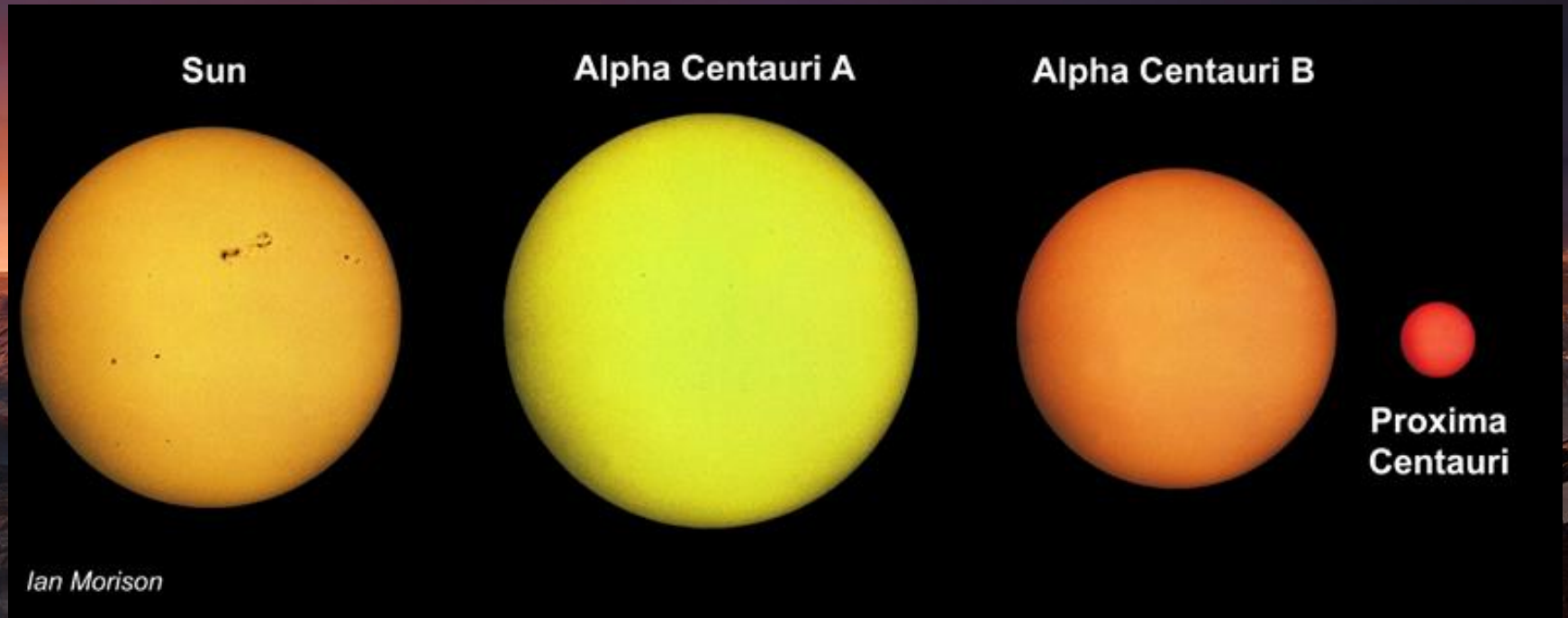
# Our nearest stellar neighbors – 4 light years away: The $\alpha$ Centauri triple system

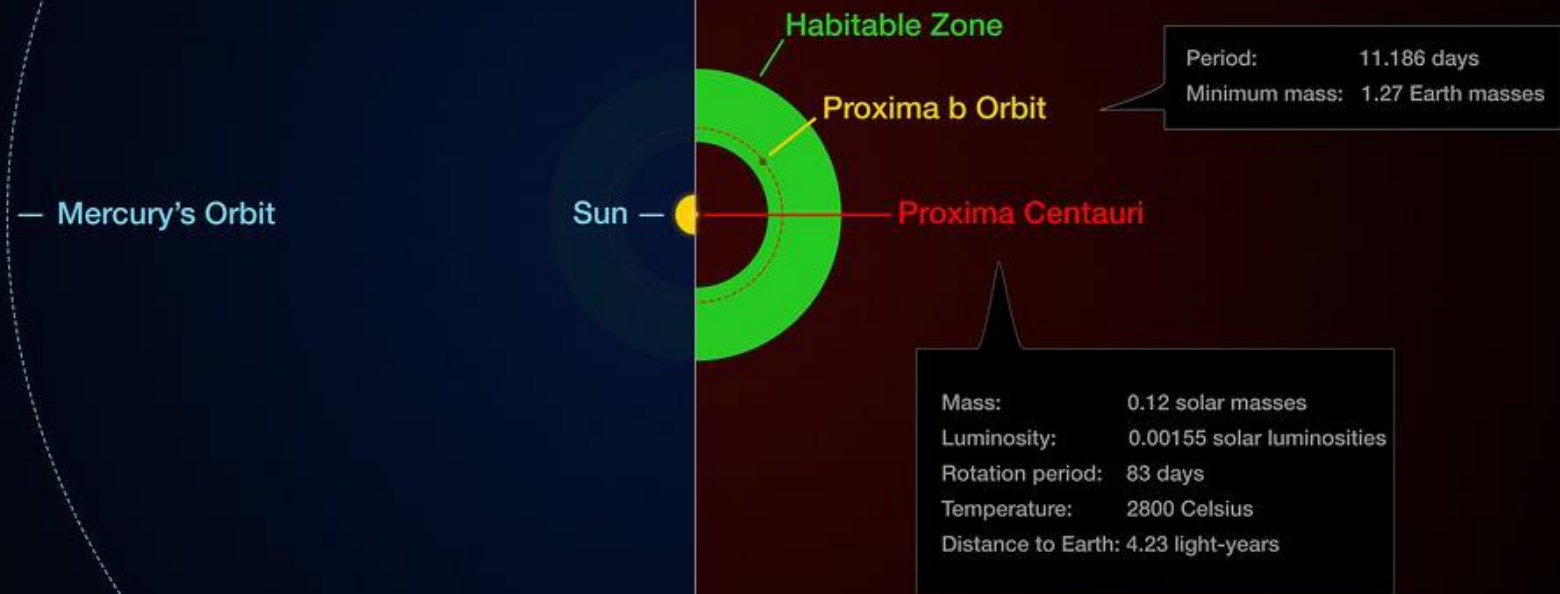
 {  $\alpha$  Cen A/Rigel Kentaurus  
 $\alpha$  Cen B

$\alpha$  Cen C/Proxima Centauri

Exoplanet Proxima Centauri b

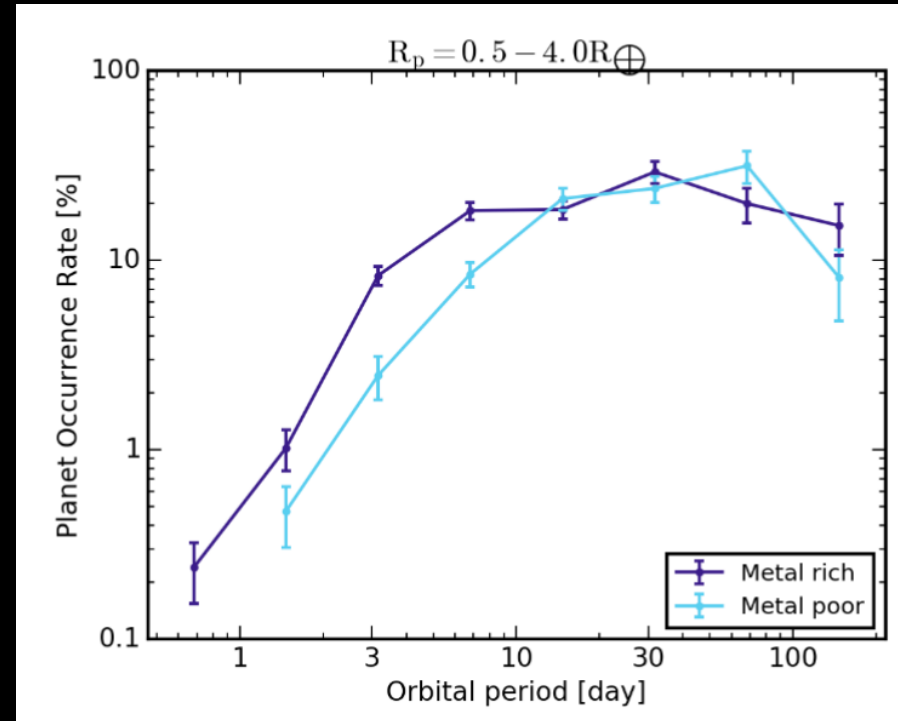
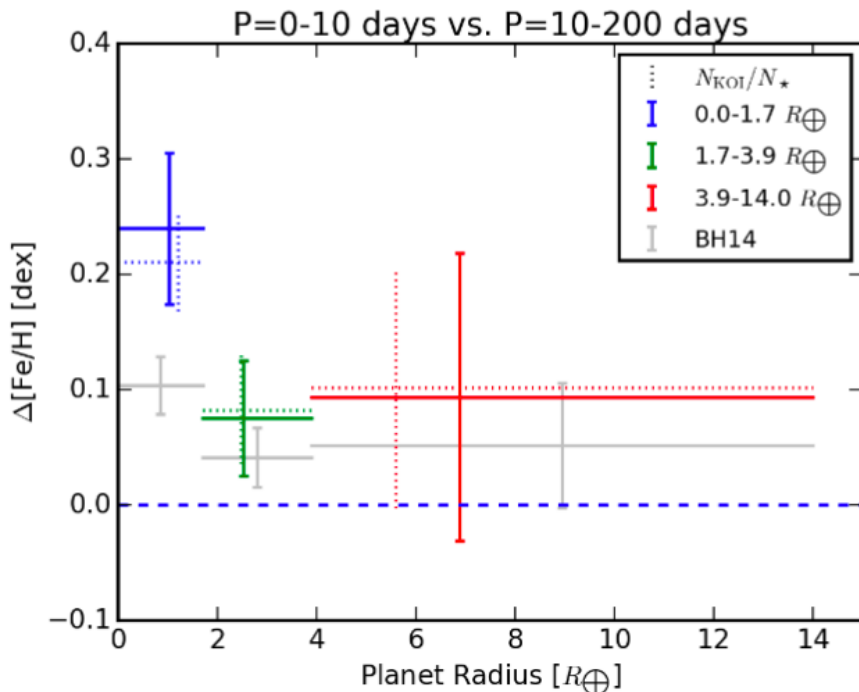
# The $\alpha$ Centauri triple system





# A Super-Solar Metallicity for Stars with Rocky Exoplanets

Mulders et al. 2016, AJ 152, 187, arXiv:1609.05898

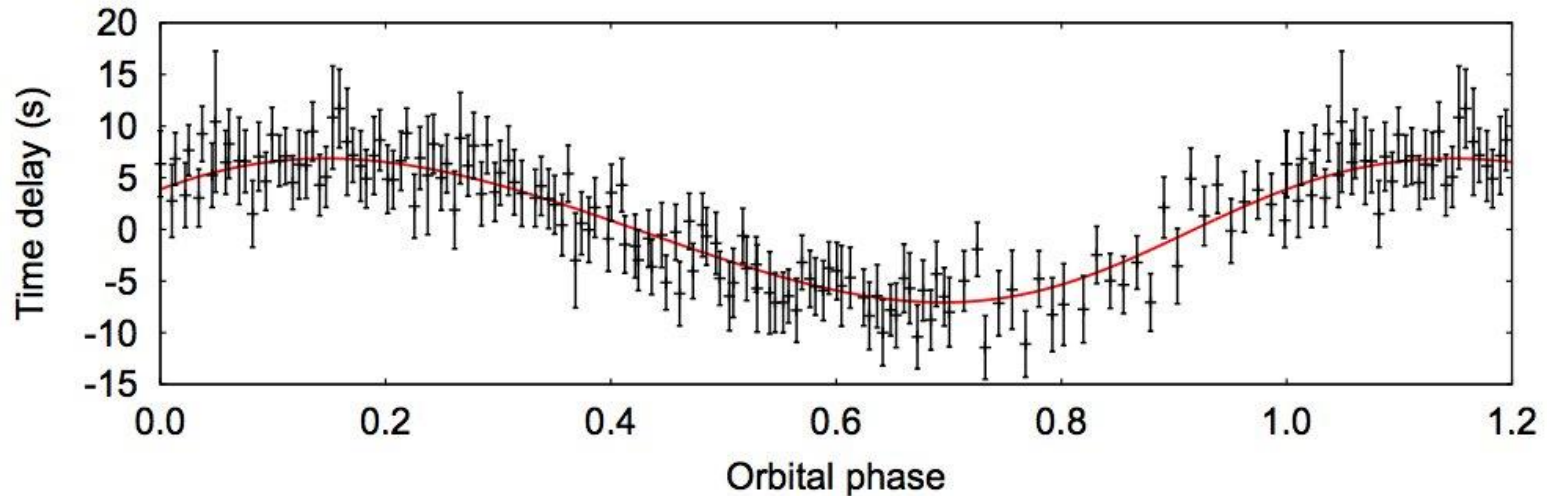


Host stars of short-period rocky planets ( $P < 10$  days,  $R < 1.7 R_{\text{Earth}}$ ) have enhanced metallicity ( $\Delta[\text{Fe}/\text{H}] = 0.25 \pm 0.07$  dex) compared to mean planet host population ( $4\sigma$  difference in distributions via K-S test).

**Metal-rich stars have 3 $\times$  higher occurrence rate of small planets ( $<4 R_{\text{Earth}}$ ) in short-period orbits ( $P < 10$  days).**

# Planet Orbiting A-type Main Sequence Star

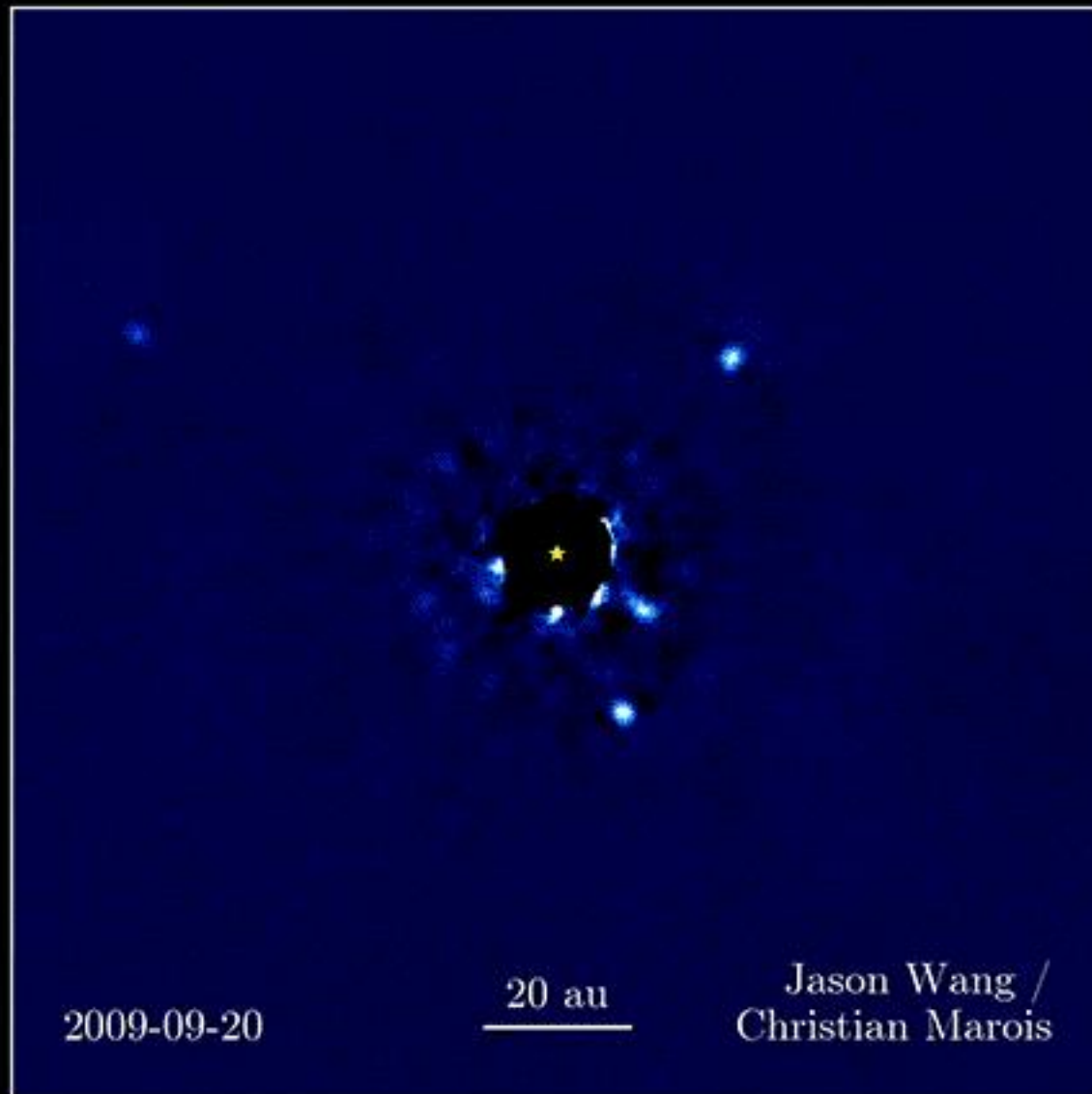
Murphy & Bedding 2016, arXiv:1608.02945 (accepted)



Planets orbiting A stars are hard to find via RV and transits due to rapid rotation, larger stellar radii, and pulsations.

This planet was identified via phase modulation of the stellar pulsations.

# HR 8799: Orbital Motion of Four Giant Planets



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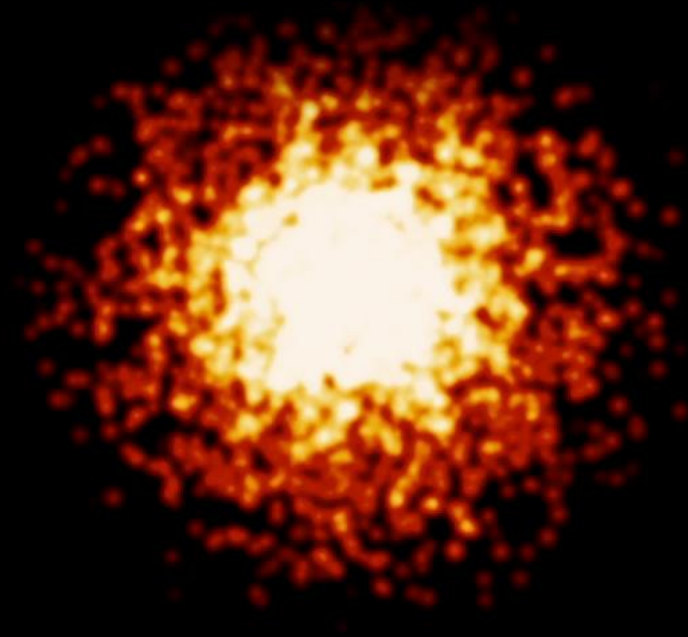
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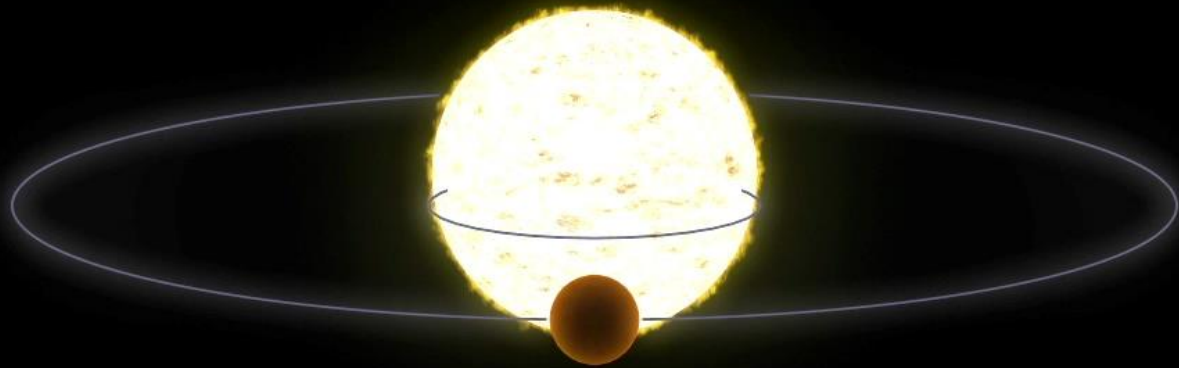
# Techniques to Detect Exoplanets

## Direct Imaging



# Techniques to Detect Exoplanets

## Astrometric Method



# Techniques to Detect Exoplanets

Doppler Spectroscopy or Radial Velocity Method



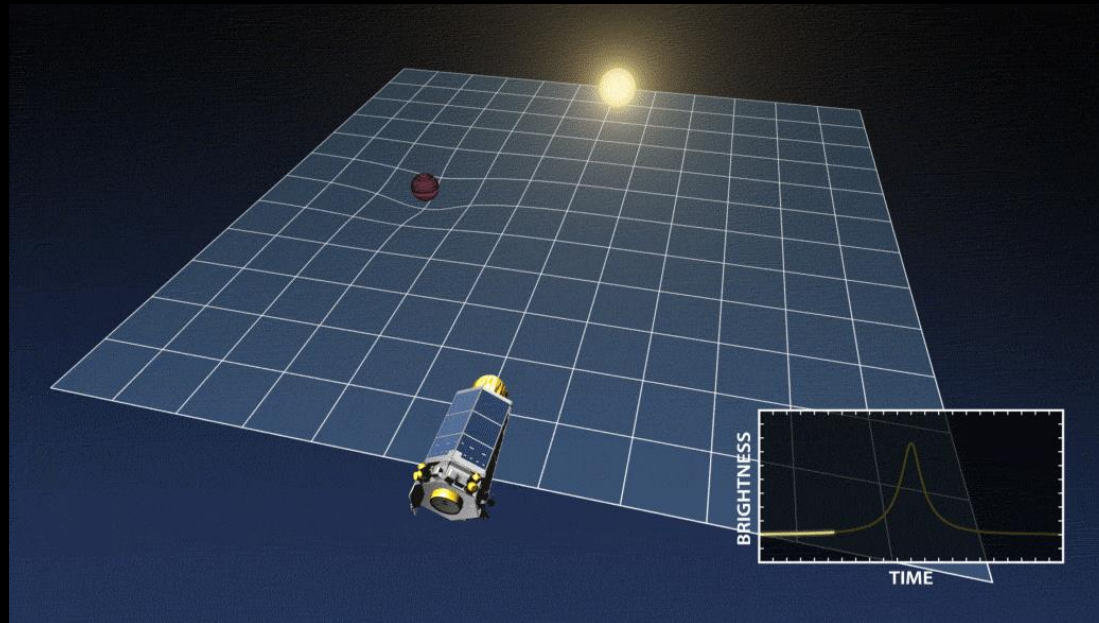
# Techniques to Detect Exoplanets

## Transit Method

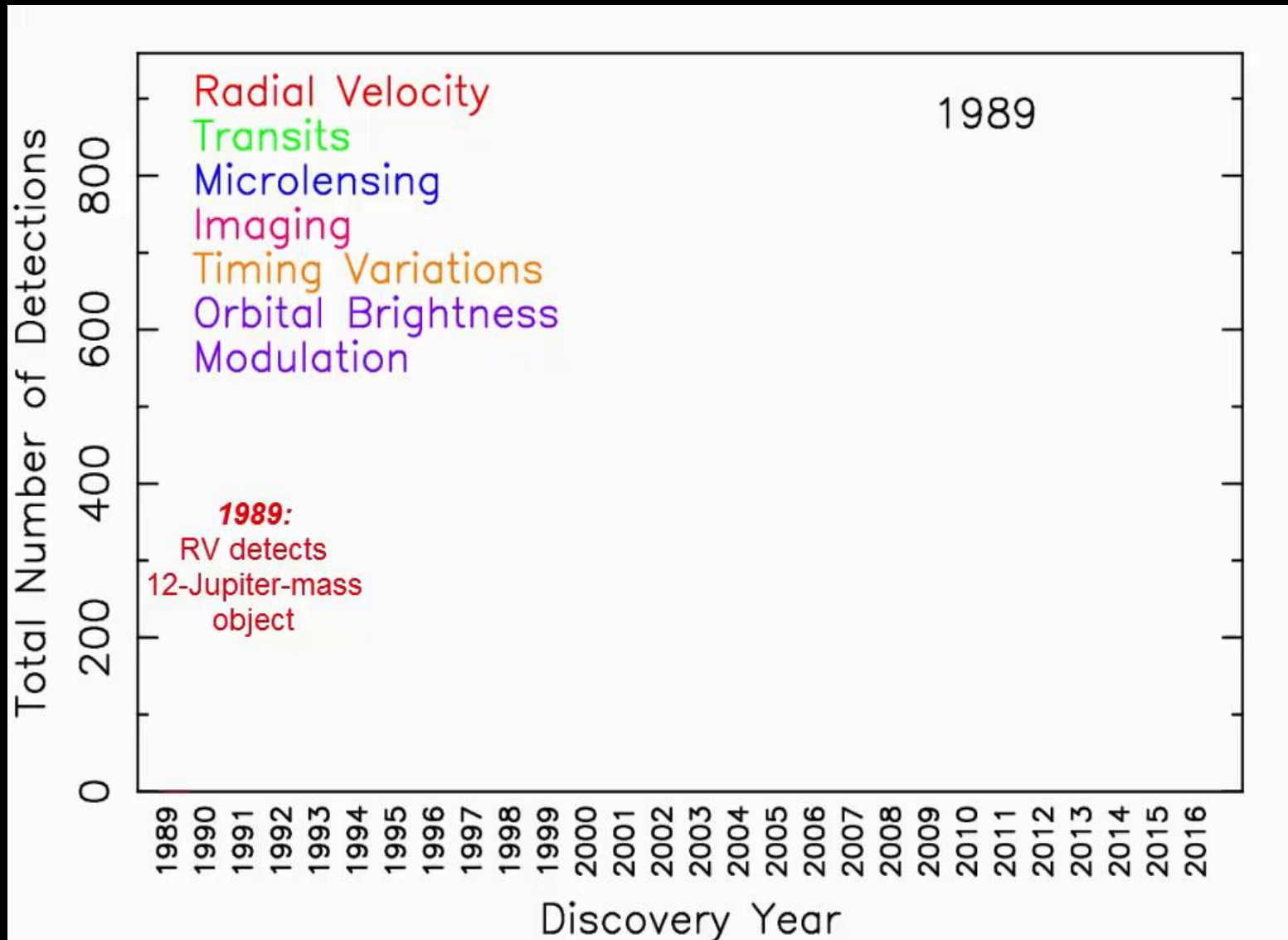


# Techniques to Detect Exoplanets

## Microlensing Method



# Confirmed Exoplanets versus Time



# Confirmed Exoplanets by Technique

Technique	Number as of 15 Feb 2017
Astrometry	1
Eclipse timing	8
Transit timing	15
Imaging	44
Microlensing	44
Orbital brightness modulation	6
Pulsar timing / pulsation	7
Stellar radial velocity	621
Transit	2732

# Exoplanet Science by Technique

Sample	Planet Radius	Planet Mass	Planet Orbit	Characterize Atmosphere	System context view
Radial Velocity	No	Lower limit	Yes	No	Planets within $\sim < 5$ AU
Transit	Yes	Yes if RV, or if TT varies	Yes if RV	Yes for larger planets & scale heights	Coplanar & short orbital period planets
$\mu$ Lensing	No	Yes	partially	No	Usually no
Imaging of self-luminous planets	Estimate from radiometry	Yes, estimate from theory and age	Yes	Yes	Hot planets plus all dust
Imaging of reflected light planets	Rough estimate only	No	Yes	Yes	All but the closest planets & dust
Stellar Astrometry	No	Yes	Yes	No	All but the closest planets

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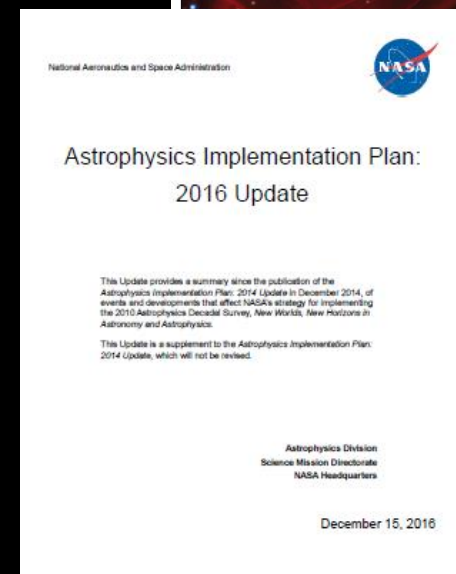
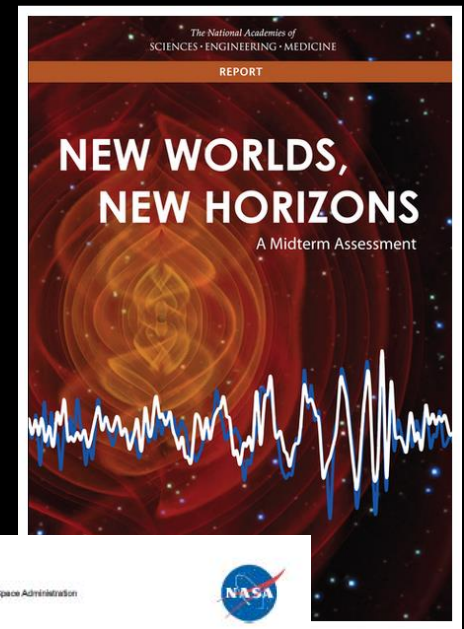
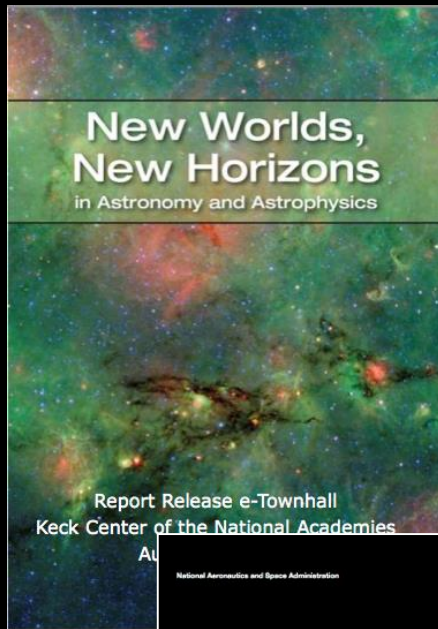
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# Astrophysics Division: Driving Documents

## Results of NWNH:

- WFIRST is top large-scale recommended activity
- NWNH technology program is top medium-scale recommended activity



# Kepler Close-Out

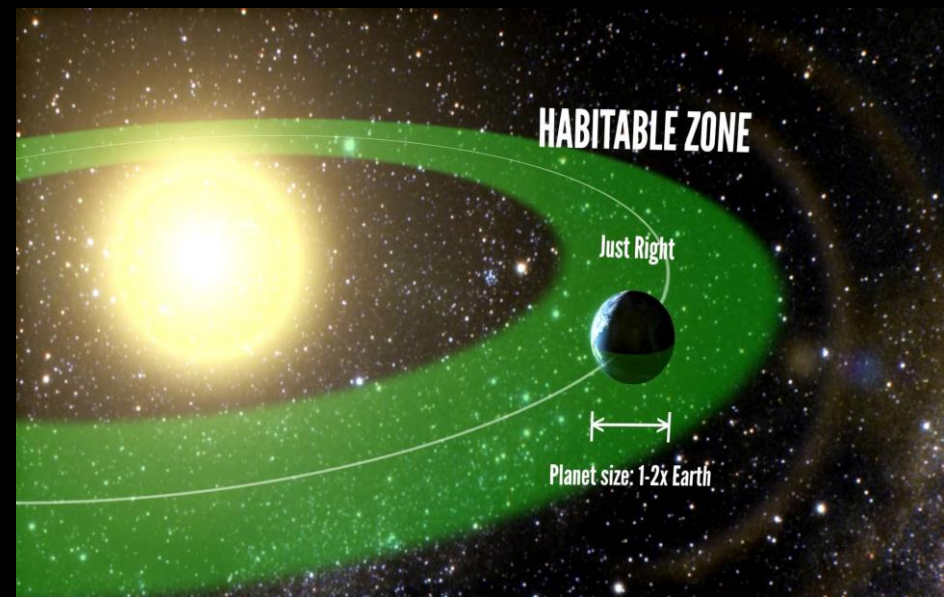
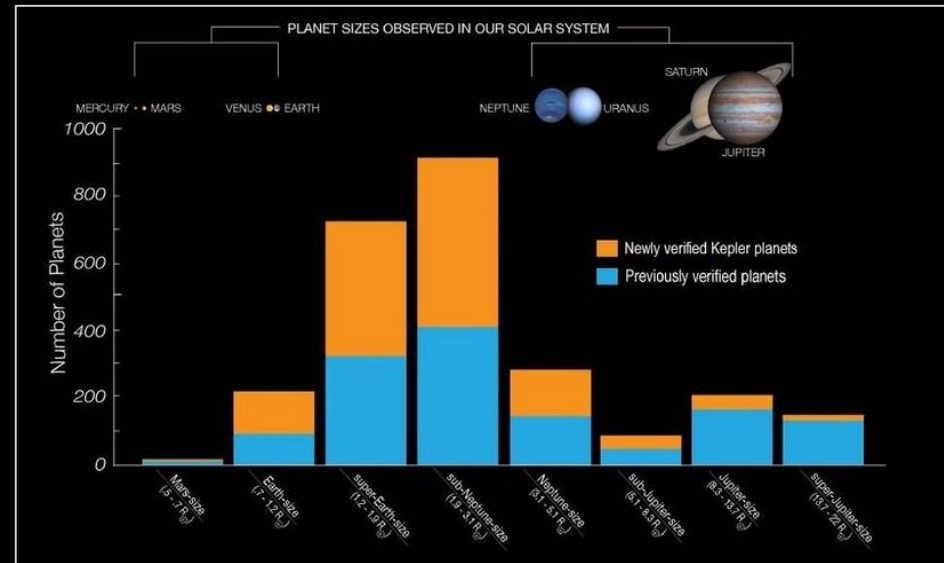
## Delivering Kepler's Legacy

- Kepler closeout and final data processing continues steadily within overall schedule margin
  - The final reprocessing of the Kepler Q0–Q17 short cadence light curves has been completed, and the files are online at MAST (8/8/16)
  - Held successful Documentation Completeness Review (10/26/2016)
  - SOC 9.3 Final Occurrence Rate Products on track (Spring 2017)



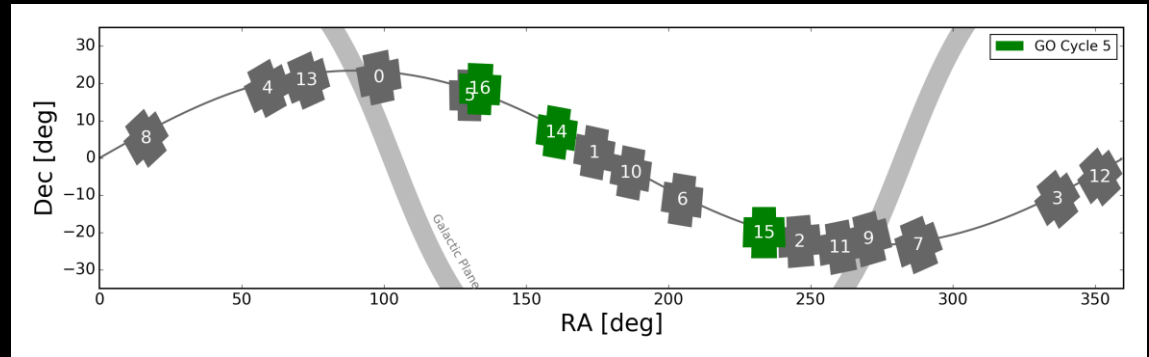
# Three Key Kepler Results

1. On average there is at least one planet for each of the stars in the night sky
2. Small planets are the most common type in the Galaxy
3. Earth-sized (0.5 to 2 Earth radii) planets in the Habitable Zone are common



# Kepler K2

## Extending the Power of Kepler to the Ecliptic

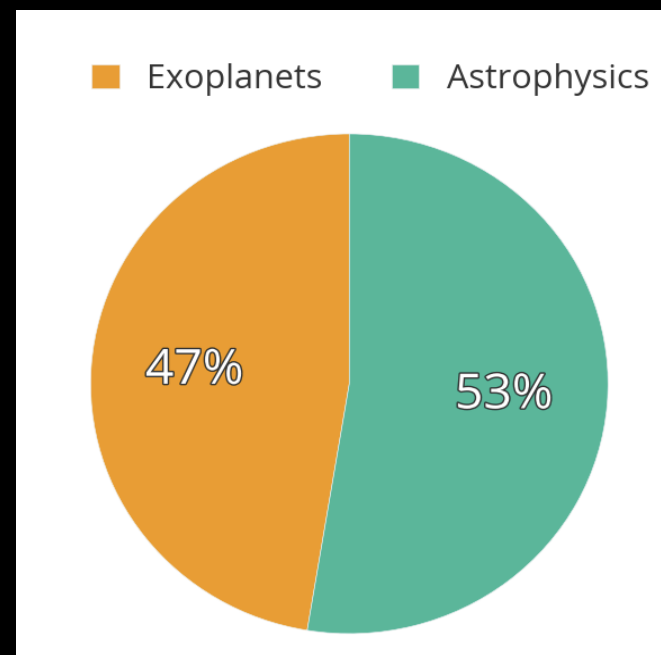
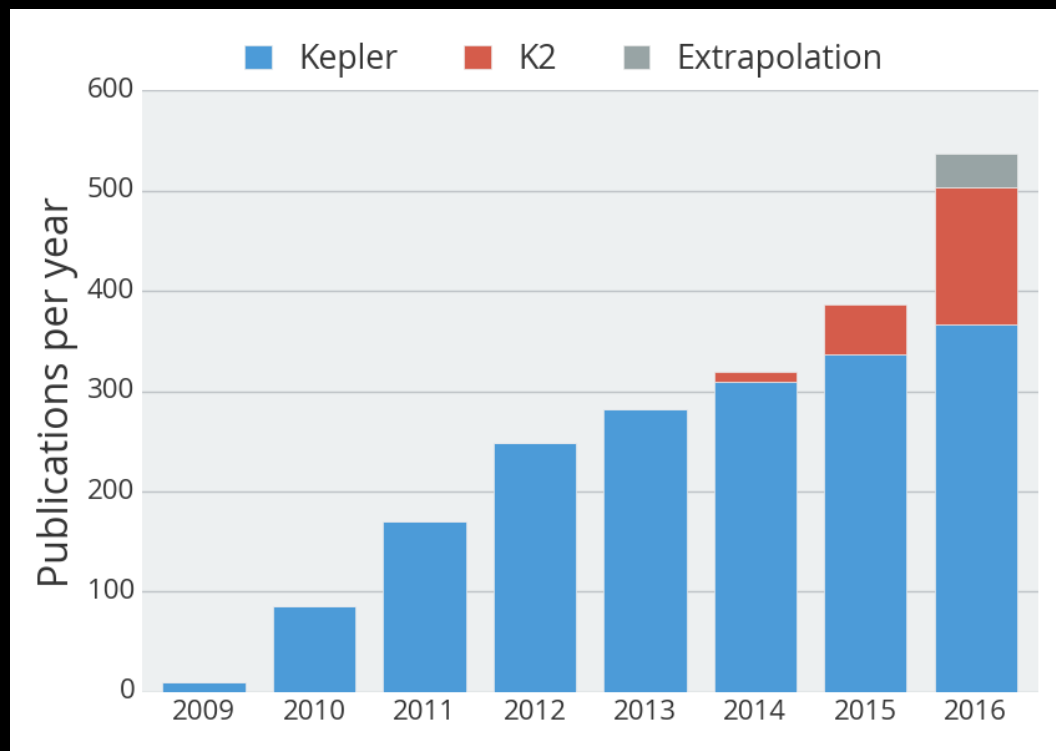


- Recent Progress
  - The C3, C4, and C5 short cadence data have been reprocessed and made available through MAST (Aug 16)
  - The Campaign 1 data has been reprocessed and is available on-line (Nov 16)
  - Processed Data released through Campaign 10 (Dec 16)
- Spacecraft remains fully operational, completed downlink of all Campaign 11 data and taking data on Campaign 12 field
- Upcoming
  - Changed the position of the field for Campaign 16 – Kepler will observe in the forward-facing direction; significant fraction of pixels dedicated to supernova science
  - Release of Microlensing results from Campaign 9

# Kepler / K2 Publication Statistics

2037 Publications, 1778 Peer-reviewed

*as of 12/7/16*

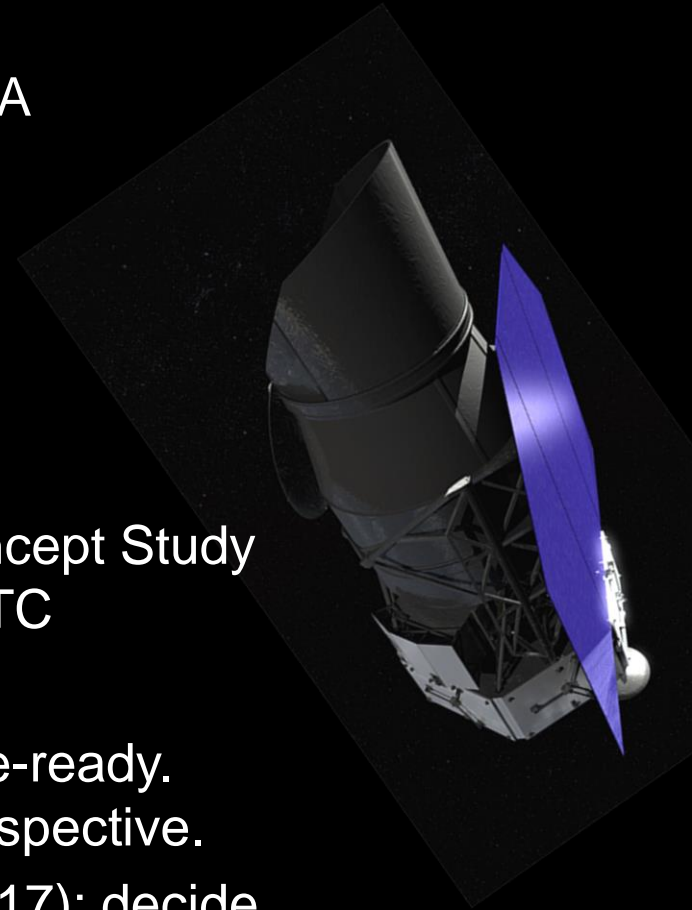


- The publication count for Kepler is 1838, that of K2 is 199
- Of the total, 965 relate to exoplanets (47%), 1071 to other areas of astrophysics (53%)

# WFIRST Update

Dark Energy, Infrared Survey... and Alien Worlds

- WFIRST is making great progress in Phase A
- All technology milestones were met on time
  - Five for IR Detector, now at TRL 6
  - Nine for Coronagraph, now at TRL 5
- Completed Acquisition Strategy Meeting in August 2016
- Wide Field Instrument Industry 6-month Concept Study with Ball Aerospace and Lockheed Martin ATC
- Reviews for SRR/MDR: July 2017
- Actively studying making WFIRST starshade-ready. First look: it's feasible from cost and risk perspective.
  - NASA Key Decision Point B (October 2017); decide whether WFIRST should be starshade-compatible
- SRB Chair appointed: Alan Bacskey, MSFC



# Large Binocular Telescope Interferometer

Measuring HZ Exozodiacal Dust, Informing Designs of Future Missions

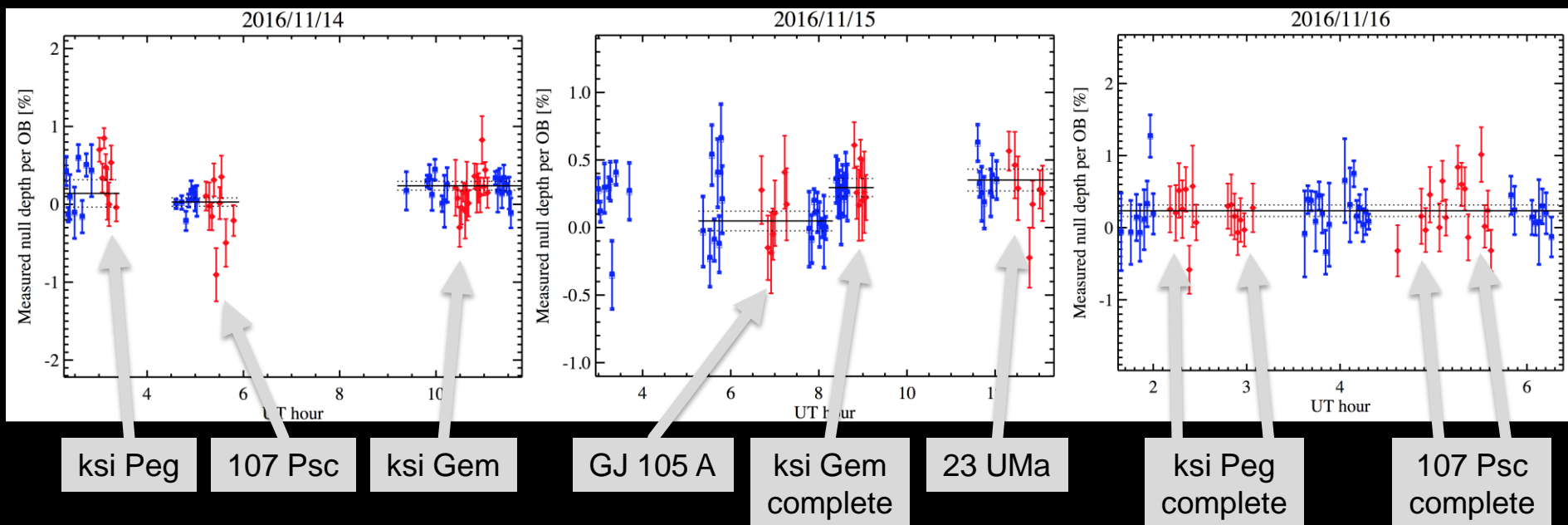
- 35-star HOSTS survey delivery planned for September 2018
- 2016B Progress: HOSTS total now at 15 stars
- Precision: 12 zodi, one star one sigma, Gives better than 2 zodi mean uncty (one sigma of ensemble).
- Will inform design of exoplanet large mission studies for 2020 Decadal Study

*Phil Hinz, PI*



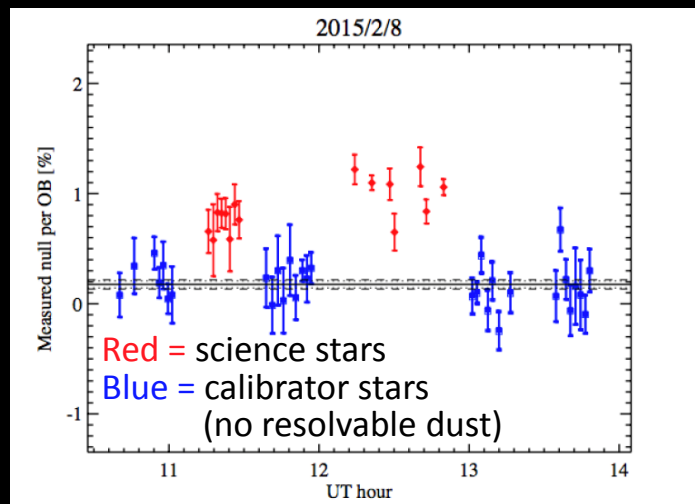
*LBTI instrument (green structure)  
mounted between the two LBT  
primary mirrors*

# Preliminary November 2016 HOSTS Data



Data are preliminary partly because the science team is 'standing down' to save costs until LBTI data are rolling in reliably. No star shows exozodiacal dust above LBTI sensitivity.

## Sample dust detection: beta Leo



The dust disk surrounding beta Leo (red data) emits 10 micron radiation not seen around calibrator stars (blue data). Measured dust brightness is  $90 \pm 8$  zodis.



- Motivation

- 2010 Decadal Survey calls for precise ground-based radial-velocity spectrometer for exoplanet discovery and characterization
- Follow-up & precursor science for current missions (K2, TESS, JWST, WFIRST)



NN-Explore Exoplanet Investigations with Doppler Spectroscopy



PennState

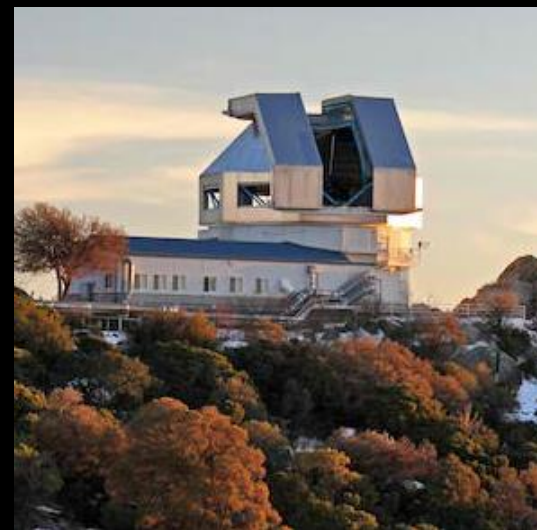
PI: S. Mahadevan

- Scope

- Extreme precision radial velocity spectrometer ( $<0.5$  m/s) for WIYN telescope development is underway
- Instrument planned to be commissioned by August 2019
- Ongoing Guest Observer program using NOAO share of telescope time for exoplanet research. Please propose!

- Status

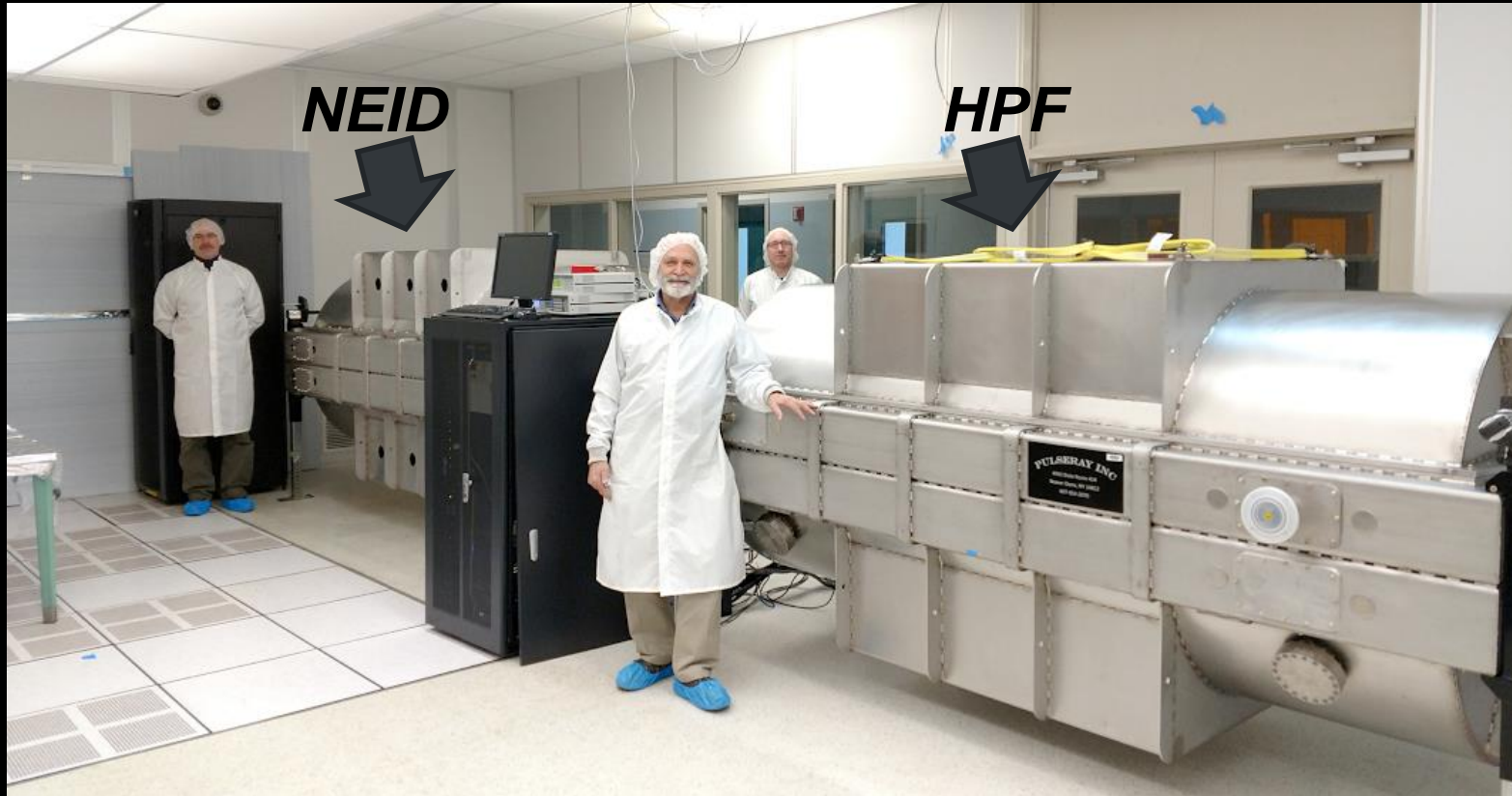
- Held Instrument Detailed Design Review, and PDR for port adapter
- Next steps: DDR for port adapter



NOAO 3.5-m WIYN Telescope,  
Kitt Peak National Observatory,  
Arizona

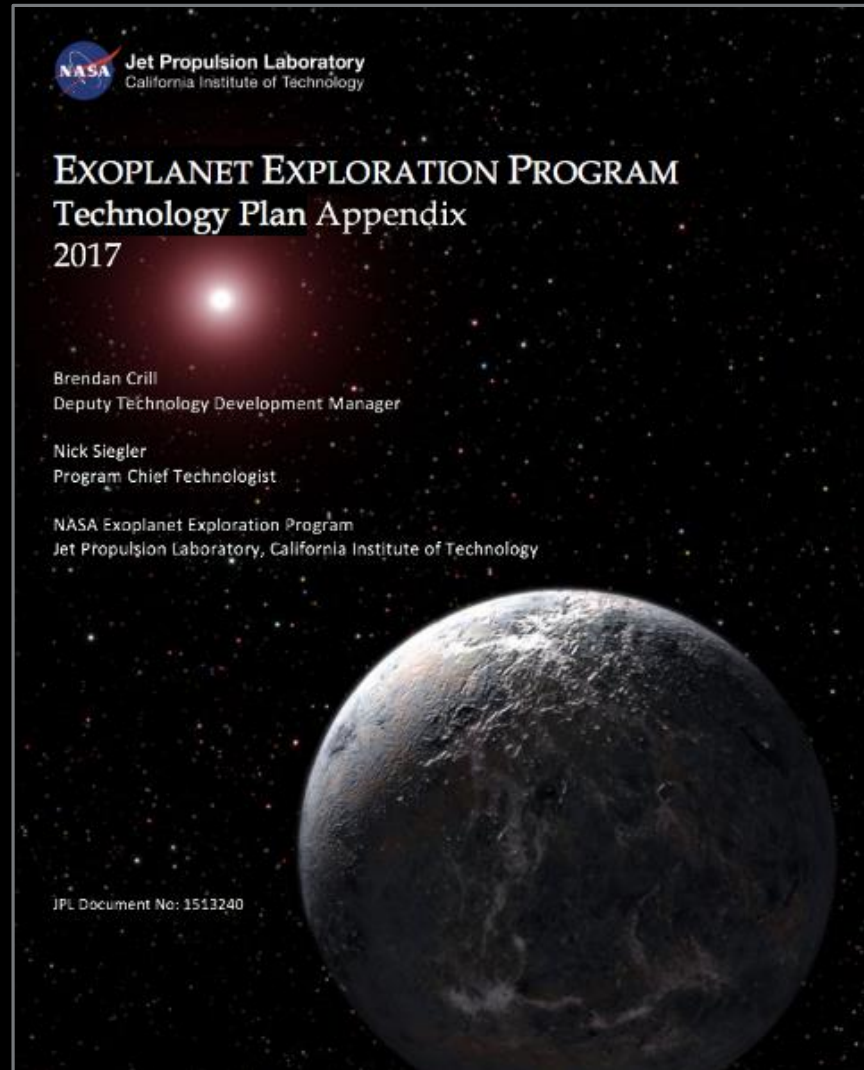
# NEID Cryostat at Penn State

Cryostat built and integrated in upstate New York



# Strategic Astrophysics Technology – TDEM

Advancing Technology Readiness towards next Decadal Survey



*Appendix revision  
published January 2017*

# Strategic Astrophysics Technology – TDEM

Reports for completed and active TDEMs: <https://exoplanets.nasa.gov/technology/>

Reviewed and approved by ExoTAC, Alan Boss (chair)

TDEMs pending final reports (by year of ROSES call in December)

- 2010
  - (Bierden) Environmental testing of MEMs DMs
  - (Helmbrecht) Environmental testing of MEMs DMs
- 2012
  - (Kasdin) Optical and mechanical verification of external occulter
- 2013
  - (Bendek) Enhanced direct imaging with astrometric mass
  - (Cash) Development of formation flying sensors
- 2014
  - (Bolcar) Next generation visible nulling
  - (Serabyn) Broadband vector vortex coronagraph
- 2015
  - (Breckinridge) Polarization in coronagraphs

# ExEP Technology Gap Lists

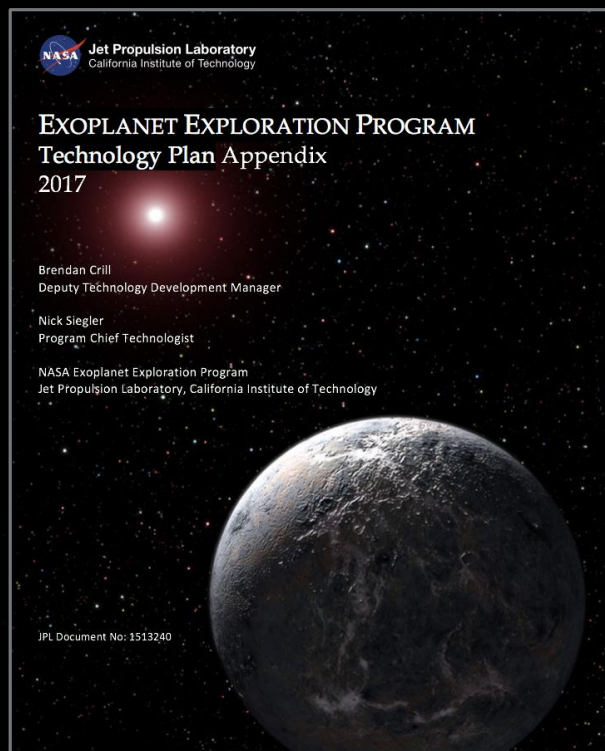
## New Process for 2017 Technology Gap List

- ExEP solicited input from the community, in particular from large mission STDTs
- ExoTAC reviewed selection and prioritization of Technology Gaps

### Starshade Technology Gap List

Table A.4 Starshade Technology Gap List

ID	Title	Description	Current	Required
S-1	Control Edge-Scattered Sunlight	Limit edge-scattered sunlight with optical petal edges that also handle stowed bending strain.	Graphite edges meet all specs except sharpness, with edge radius $\geq 10 \mu\text{m}$ .	Optical petal edges manufactured of high flexural strength material with edge radius $\leq 1 \mu\text{m}$ and reflectivity $\leq 10\%$ .
S-2	Contrast Performance Demonstration at Optical Model Validation	Experimentally validate the equations that predict the contrasts achievable with a starshade.	Experiments have validated optical diffraction models at Fresnel number of $\sim 500$ to contrasts of $3 \times 10^{-10}$ at 632 nm.	Experimentally validate models of starlight suppression to $\leq 3 \times 10^{-11}$ at Fresnel numbers $\leq 50$ over 510-825 nm bandpass.
S-3	Lateral Formation Flying Sensing Accuracy	Demonstrate lateral formation flying sensing accuracy consistent with keeping telescope in starshade's dark shadow.	Centroid accuracy $\geq 1\%$ is common. Simulations have shown that sensing and GN&C is tractable, though sensing demonstration of lateral control has not yet been performed.	Demonstrate sensing lateral errors $\leq 0.20\text{m}$ at scaled flight separations and estimated centroid positions $\leq 0.3\%$ of optical resolution. Control algorithms demonstrated with lateral control errors $\leq 1\text{m}$ .
S-4	Flight-Like Petal Fabrication and Deployment	Demonstrate a high-fidelity, flight-like starshade petal and its unfurling mechanism.	Prototype petal that meets optical edge position tolerances has been demonstrated.	Demonstrate a fully integrated petal, including blankets, edges, and deployment control interfaces. Demonstrate a flight-like unfurling mechanism.
S-5	Inner Disk Deployment	Demonstrate that a starshade can be autonomously deployed to within the budgeted tolerances.	Demonstrated deployment tolerances with 12m heritage Astromesh antenna with four petals, no blankets, no outrigger struts, and no launch restraint.	Demonstrate deployment tolerances with flight-like, minimum half-scale inner disk, with simulated petals, blankets, and interfaces to launch restraint.

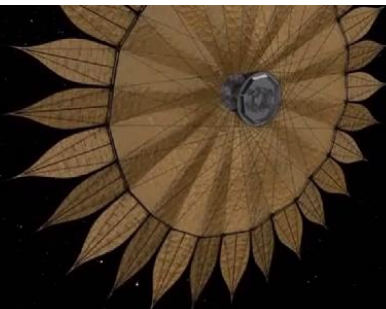


### Coronagraph Technology Gap List

Table A.3 Coronagraph Technology Gap List

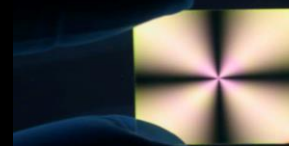
ID	Title	Description	Current	Required
C-1	Specialized Coronagraph Optics	Masks, apodizers, or beam-shaping optics to provide starlight suppression and planet detection capability.	A linear mask design has yielded $3.2 \times 10^{-10}$ mean raw contrast from $3-16 \lambda/D$ with 10% bandwidth using an unobscured pupil in a static lab demonstration.	Circularly symmetric masks achieving $\leq 1 \times 10^{-10}$ contrast with IWA $\leq 3 \lambda/D$ and $\geq 10\%$ bandwidth on obscured or segmented pupils.
C-2*	Low-Order Wavefront Sensing & Control	Beam jitter and slowly varying large-scale (low-order) optical aberrations may obscure the detection of an exoplanet.	Tip/tilt errors have been sensed and corrected in a stable vacuum environment with a stability of $10^{-3} \lambda$ rms at sub-Hz frequencies.	Tip/tilt, focus, astigmatism, and coma sensed and corrected simultaneously to $10^{-3} \lambda$ ( $\sim 10\%$ of pm) rms to maintain raw contrasts of $\leq 1 \times 10^{-10}$ in a simulated dynamic testing environment.
C-3*	Large-Format Ultra-Low Noise Visible Detectors	Low-noise visible detectors for faint exoplanet characterization with an Integral Field Spectrograph.	Read noise of $< 1 e^-/\text{pixel}$ has been demonstrated with EMCCDs in a $1k \times 1k$ format with standard read-out electronics.	Read noise $< 0.1 e^-/\text{pixel}$ in a $\geq 4k \times 4k$ format validated for a space radiation environment and flight-accepted electronics.
C-4*	Large-Format Deformable Mirrors	Maturation of deformable mirror technology toward flight readiness.	Electrostrictive $64 \times 64$ DMs have been demonstrated to meet $\leq 10^{-9}$ contrasts in a vacuum environment and 10% bandwidth.	$\geq 64 \times 64$ DMs with flight-like electronics capable of wavefront correction to $\leq 10^{-10}$ contrasts. Full environmental testing validation.
C-5	Efficient Contrast Convergence	Rate at which wavefront control methods achieve $10^{-10}$ contrast.	Model and measurement uncertainties limit wavefront control convergence and require many tens to hundreds of iterations to get to $10^{-10}$ contrast from an arbitrary initial wavefront.	Wavefront control methods that enable convergence to $10^{-10}$ contrast ratios in fewer iterations ( $10-20$ ).
C-6*	Post-Data Processing	Techniques are needed to characterize exoplanet spectra from residual speckle noise for typical targets.	Few 100x speckle suppression has been achieved by HST and by ground-based AO telescopes in the NIR and in contrast regimes of $10^{-5}$ to $10^{-6}$ , dominated by phase errors.	A 10-fold improvement over the raw contrast of $\sim 10^{-6}$ in the visible where amplitude errors are expected to no longer be negligible with respect to phase errors.

\*Topic being addressed by directed-technology development for the WFIRST/AFTA coronagraph. Consequently, coronagraph technologies that will be substantially advanced under the WFIRST/AFTA technology development are not eligible for TDEMs.



Appendix revision  
published January 2017

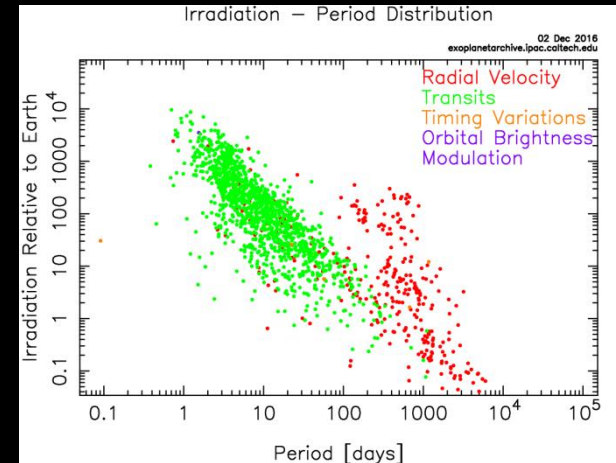
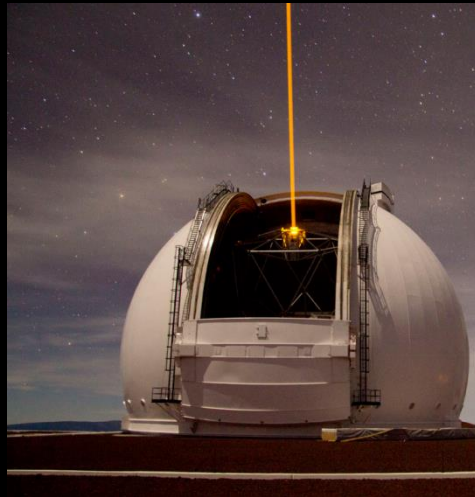
<https://exoplanets.nasa.gov/technology/>



# NASA Exoplanet Science Institute (NExSci) Update



- Sagan Summer School, July 2016  
“Is there a Planet in my Data?”
- Sagan Summer School, August 2017  
“Microlensing in the Era of WFIRST”
- NASA/Keck times (90 nights/yr) supports Exoplanets, Cosmic Origins, Physics of the Cosmos and Solar System Science
- Exoplanet Archive tracks exoplanet population and Kepler pipeline products
- ExoFOP supports Kepler & K2 sources follow-up



Program Overview

Science Updates

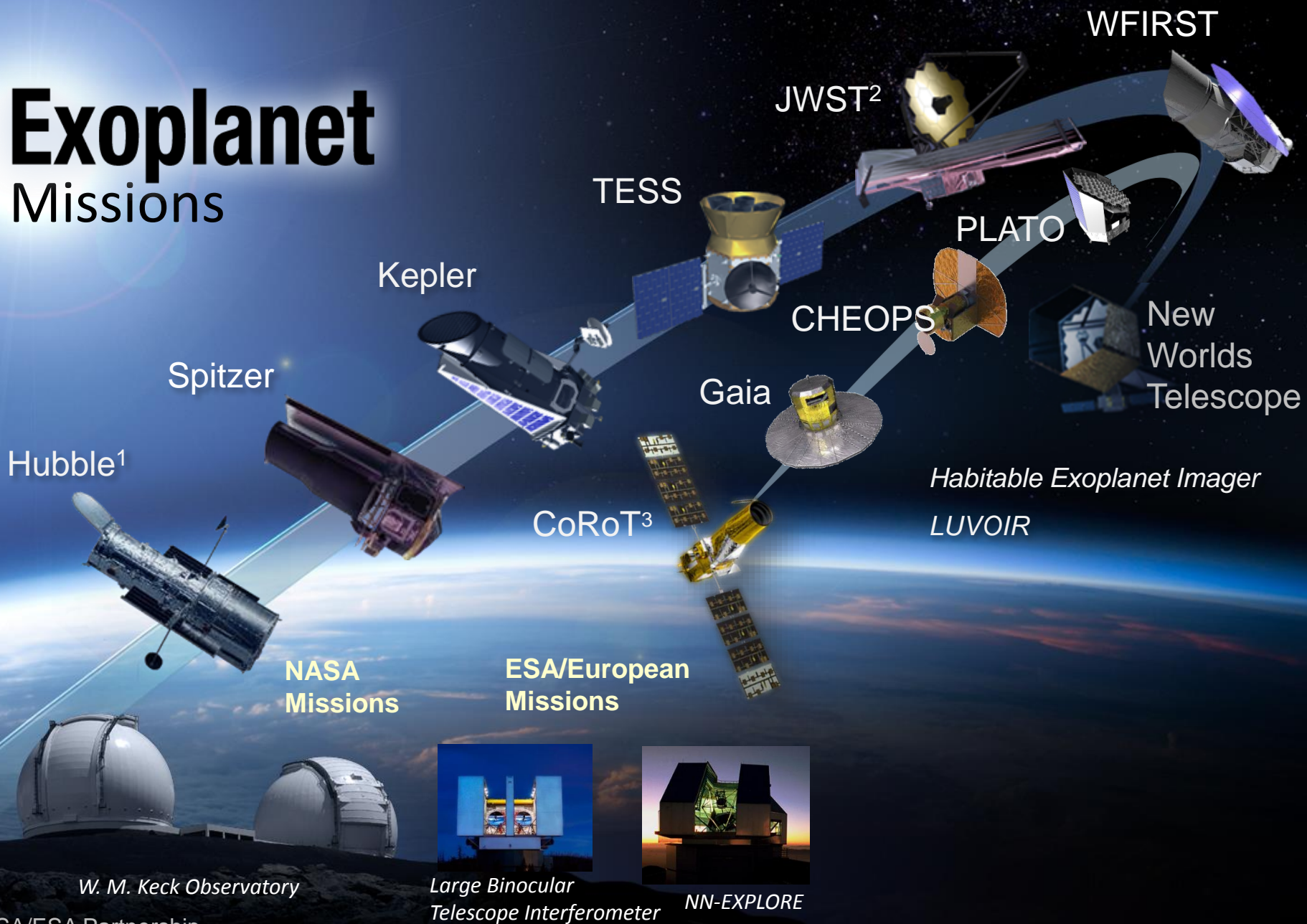
How Do We Discover & Characterize Exoplanets?

Progress towards 2010 Decadal Survey Priorities

Plan Forward: Science and Technology

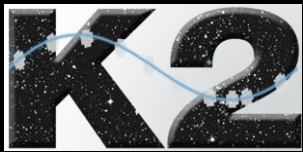
ExoComm: Show Me the Planets!

# Exoplanet Missions

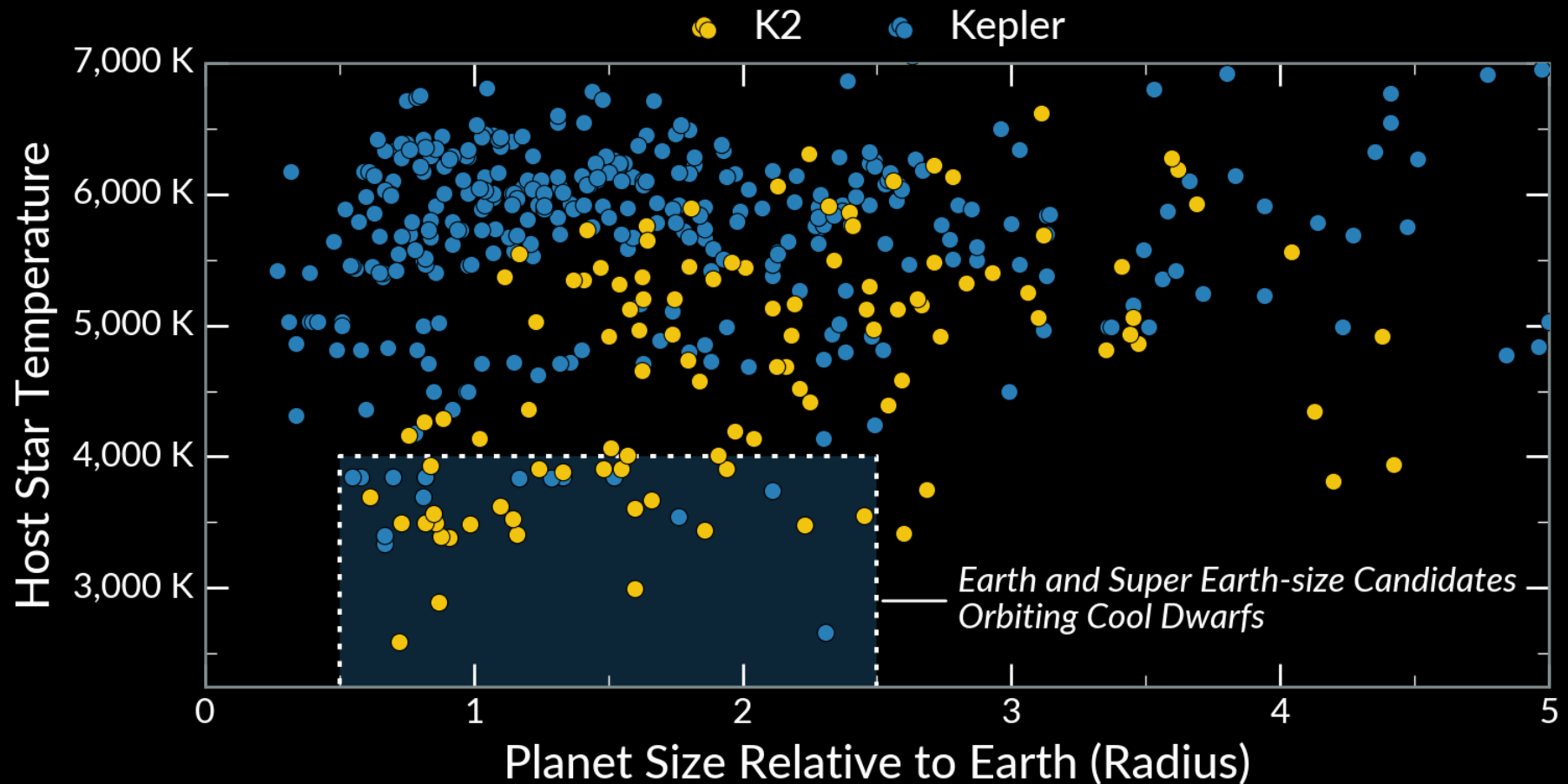


**Ground Telescopes with NASA participation**

- <sup>1</sup> NASA/ESA Partnership
- <sup>2</sup> NASA/ESA/CSA Partnership
- <sup>3</sup> CNES/ESA

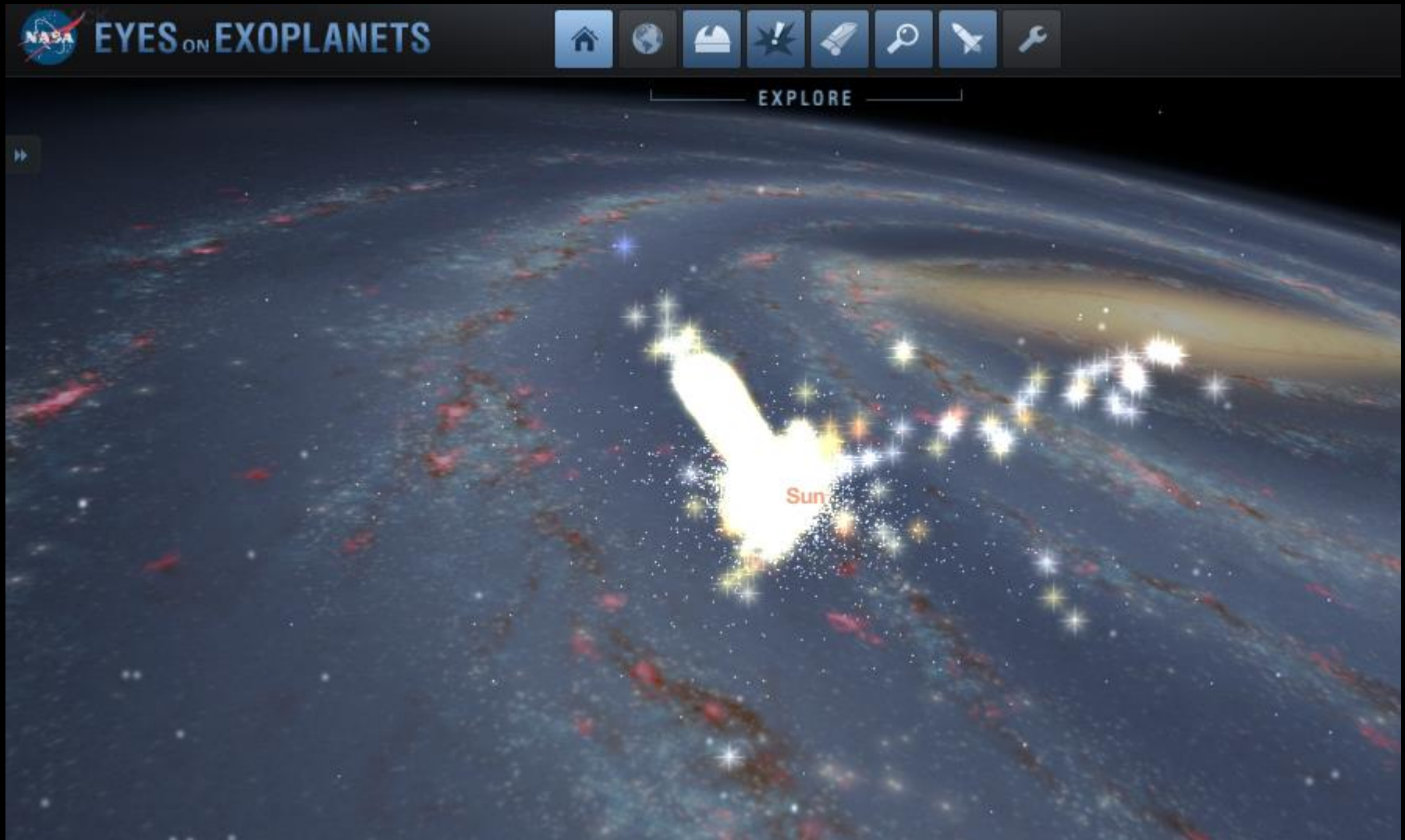


## Planet Candidates for Atmospheric Characterization ( $K_s < 11$ )



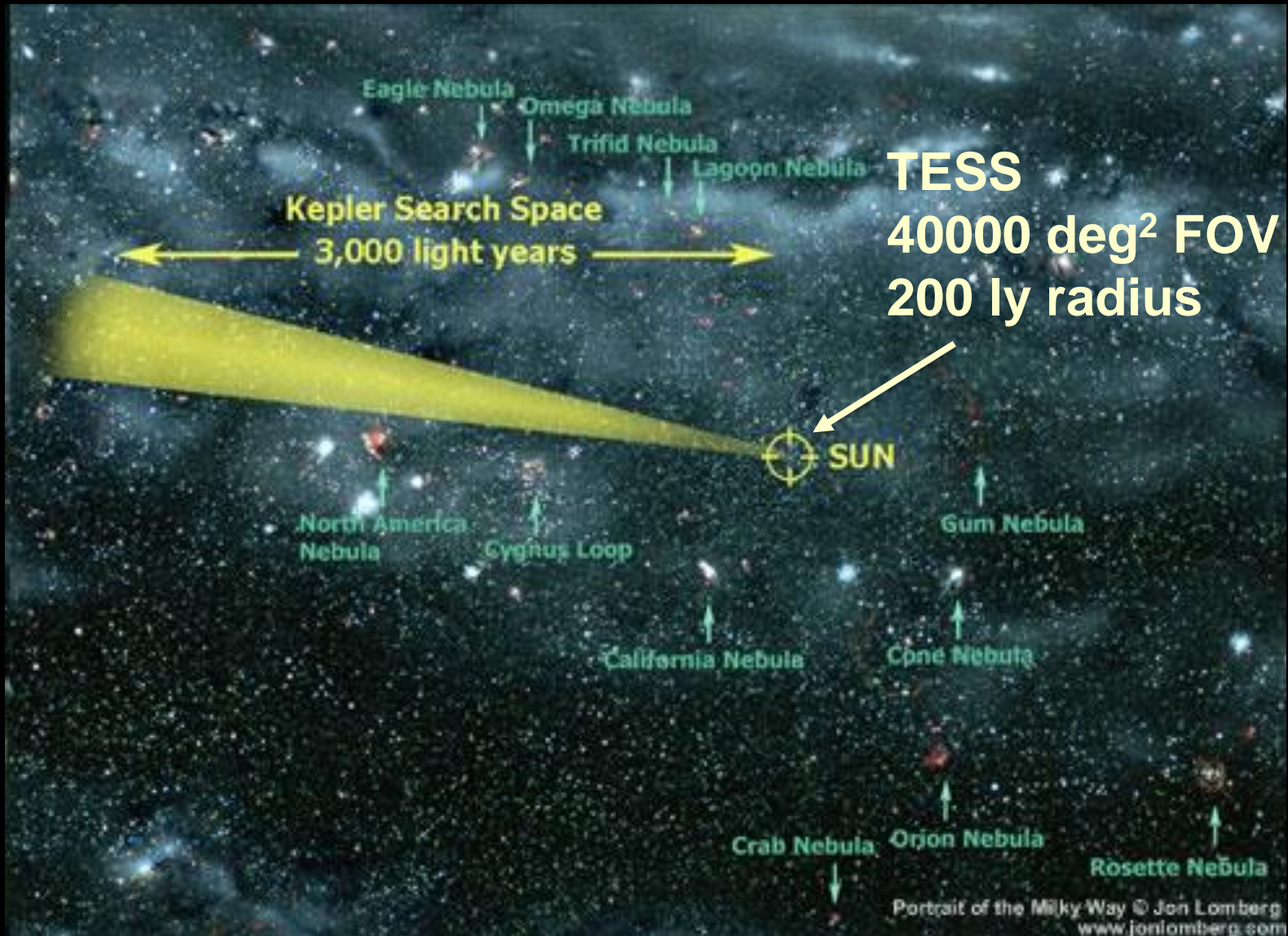
# Exoplanet: Confirmed and Candidates

Visualization from *Eyes on Exoplanets*



# TESS Will Survey Nearby Stars

Provides Bright Targets for JWST Transit Spectroscopy



# WFIRST Microlensing Census for Exoplanets

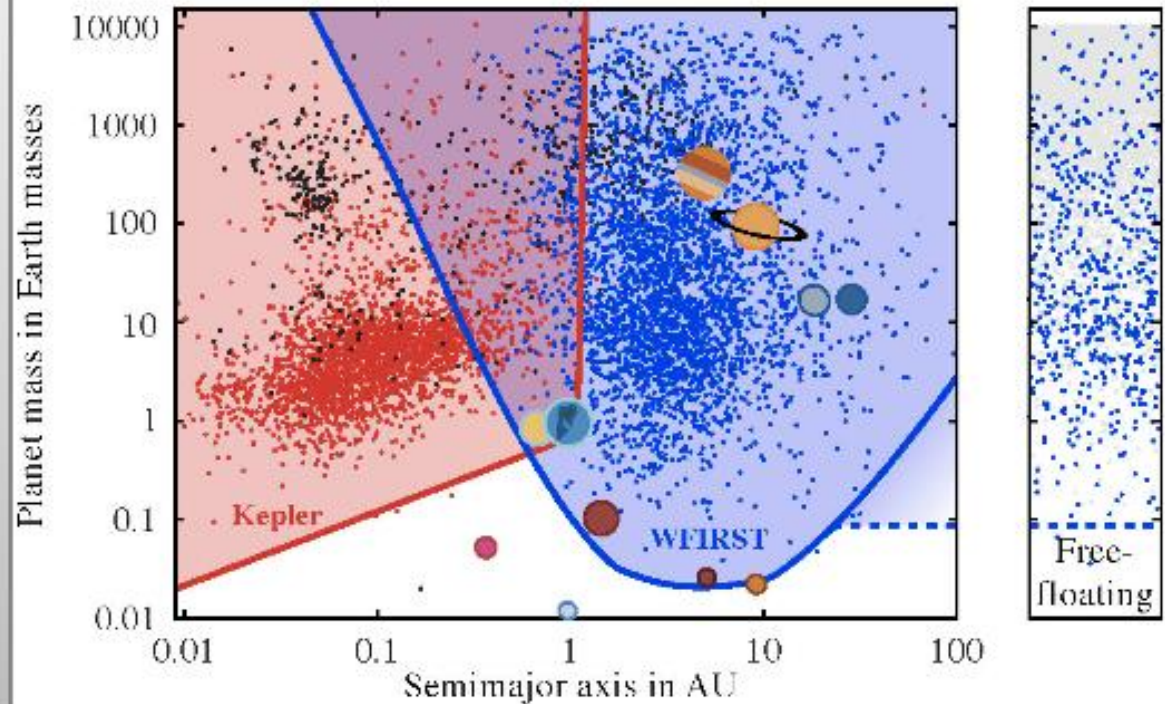


Together, Kepler and WFIRST-AFTA complete the statistical census of planetary systems in the Galaxy.



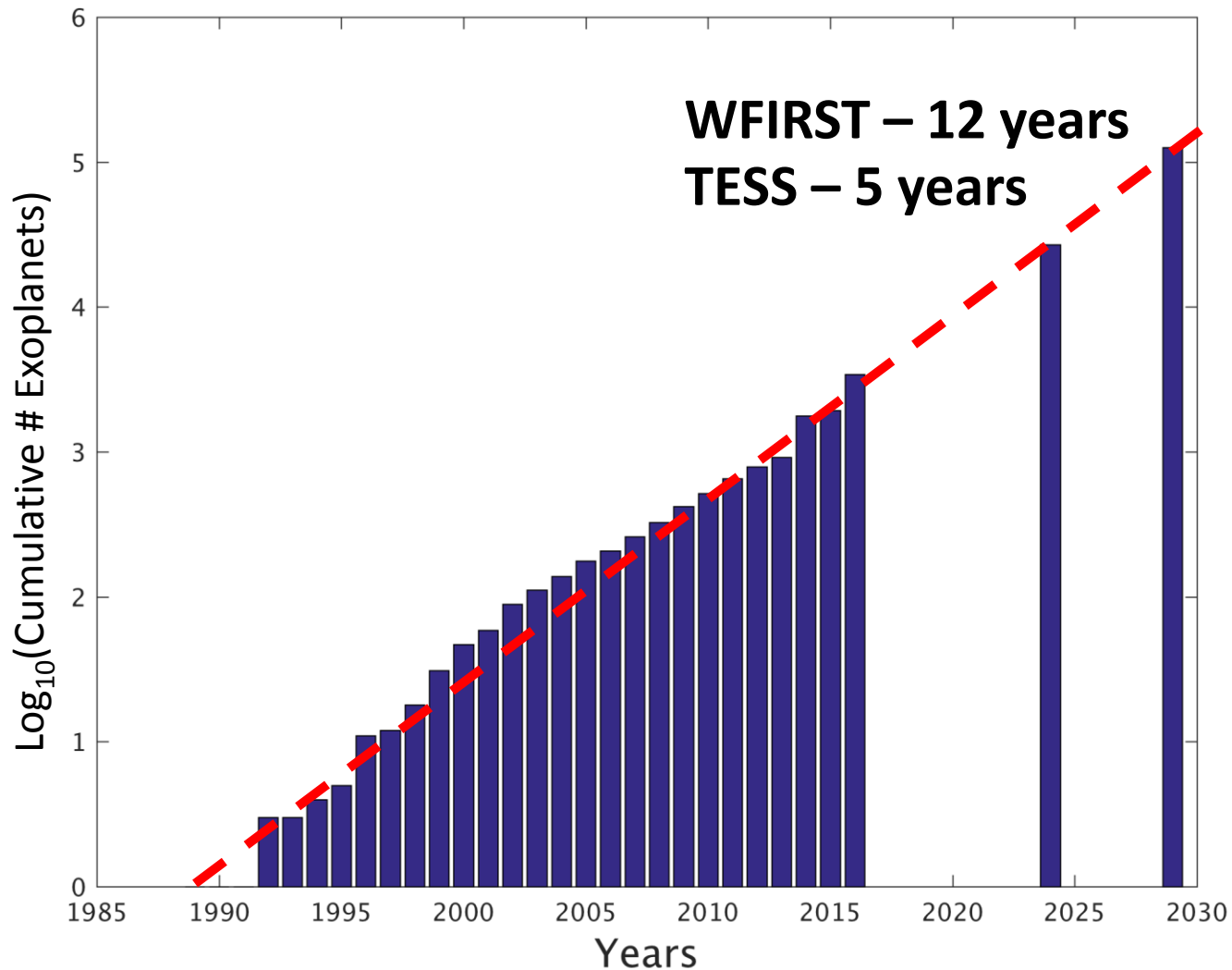
## WFIRST-AFTA will:

- Detect 2800 planets, with orbits from the habitable zone outward, and masses down to a few times the mass of the Moon.
- Be sensitive to analogs of all the solar system's planets except Mercury.
- Measure the abundance of free-floating planets in the Galaxy with masses down to the mass of Mars

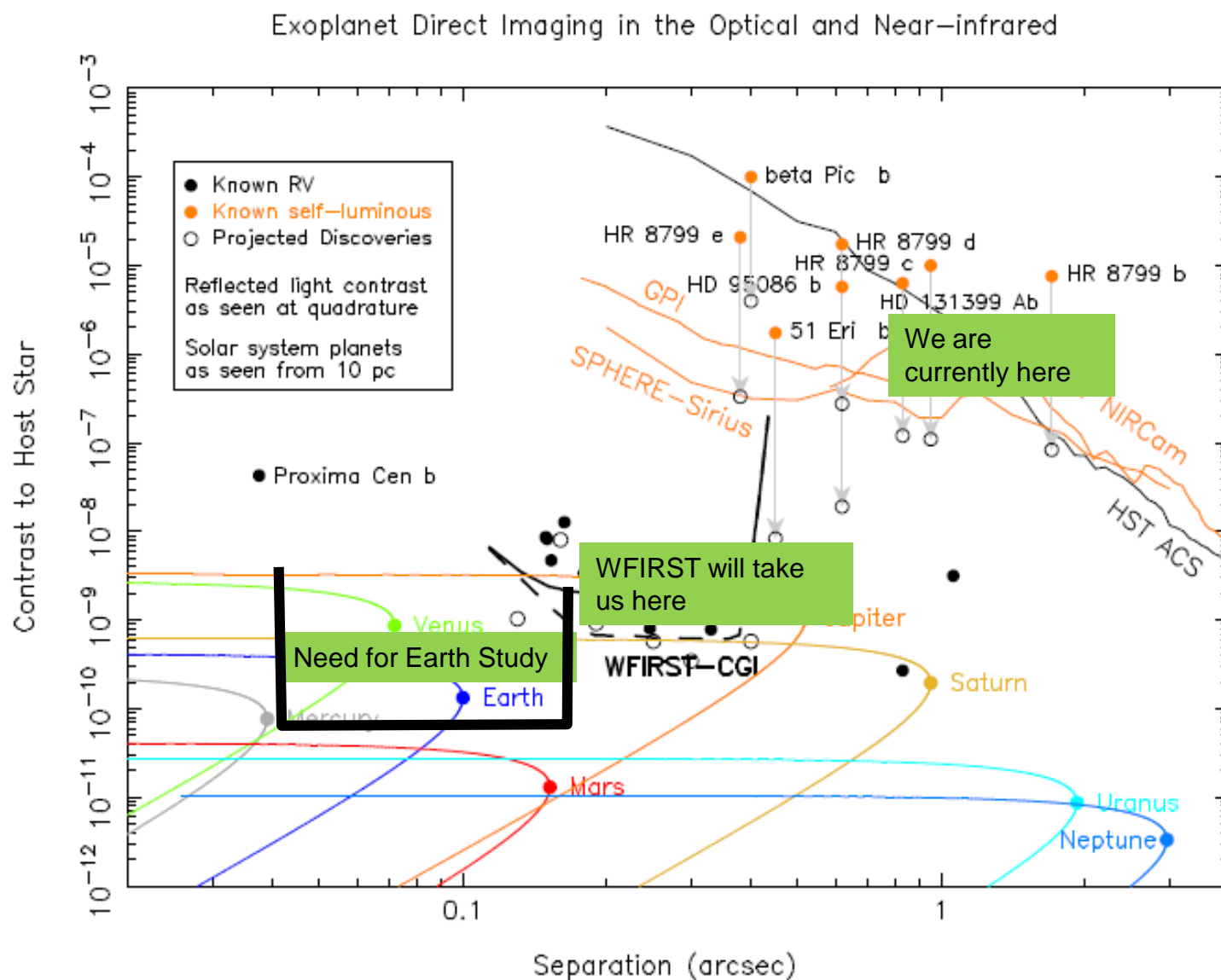


*Credit: D. Bennett, M. Penny*

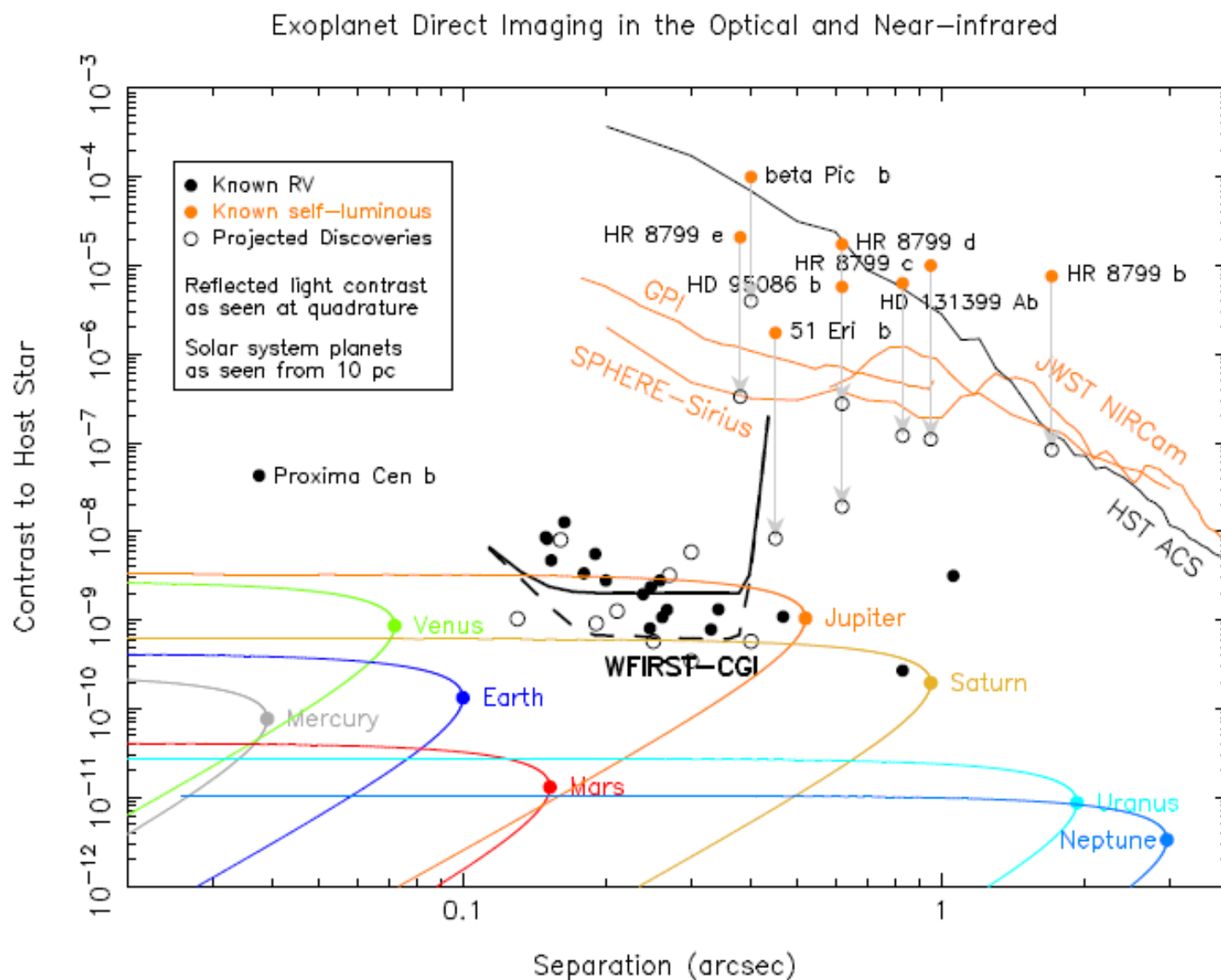
# How Much Longer Can Mamajek's Law Last?



# Exoplanet Direct Imaging

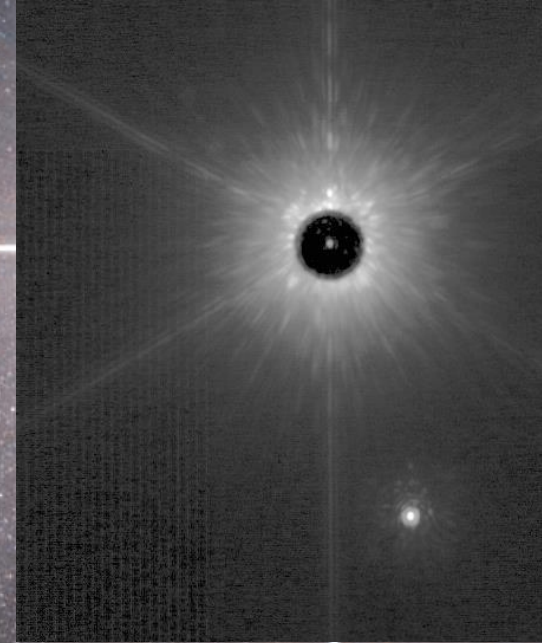
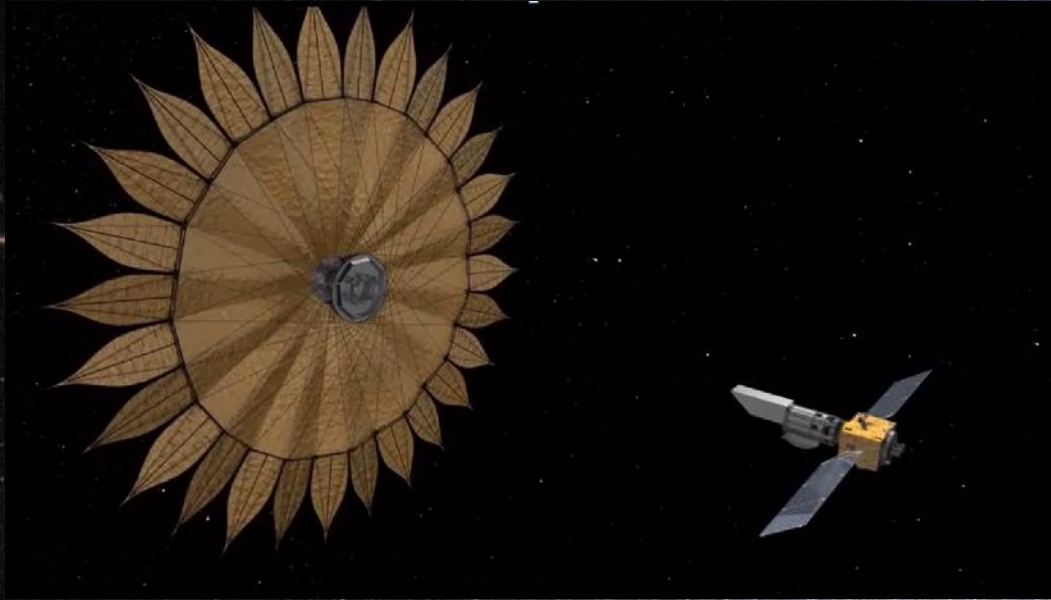


# Exoplanet Direct Imaging



# Starlight Suppression is the Key Technology in the Search for Life on Earth-Size Exoplanets

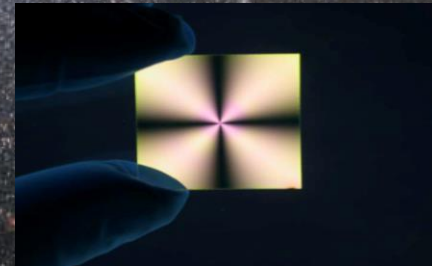
## External Occulters (Starshades)



## Nulling Interferometry

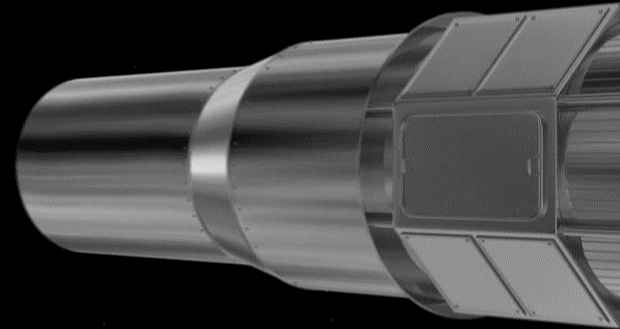


## Internal Occulters (Coronagraphs)



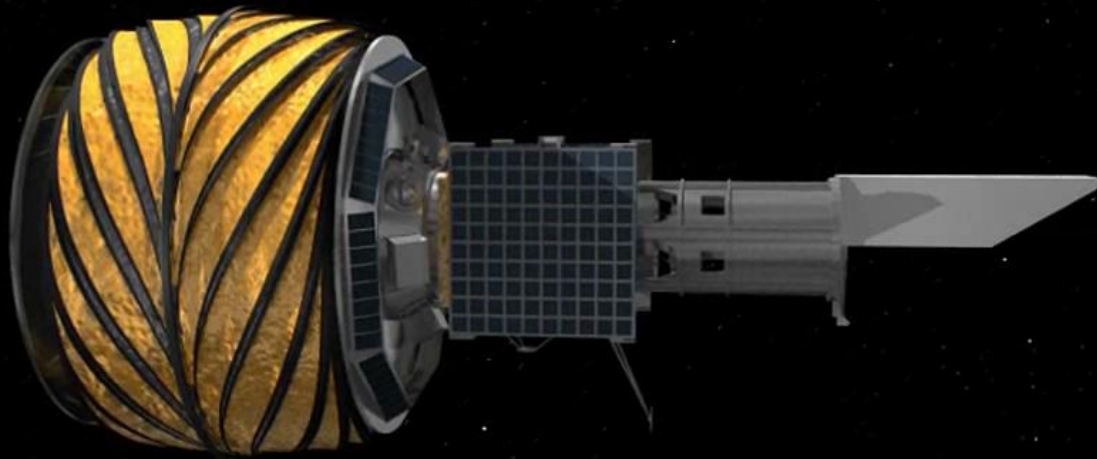
# Internal Coronagraph

Controls Diffraction to Reveal Exoplanets in “Dark Hole”



# Starshade (External Occulter)

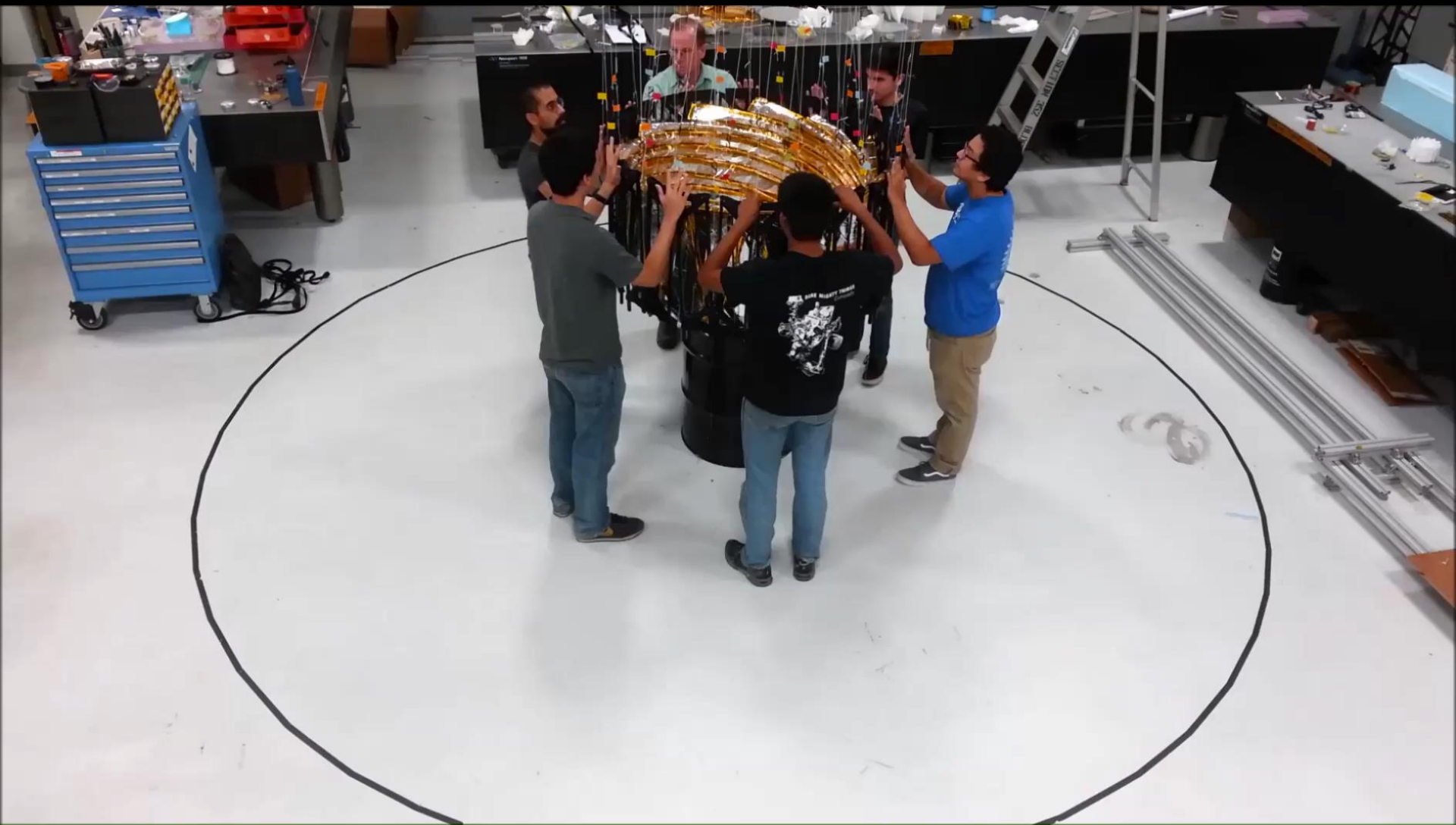
Blocks Starlight, Controls Diffraction prior to Entering Telescope



# Early Inner Disk Deployment Trials at JPL

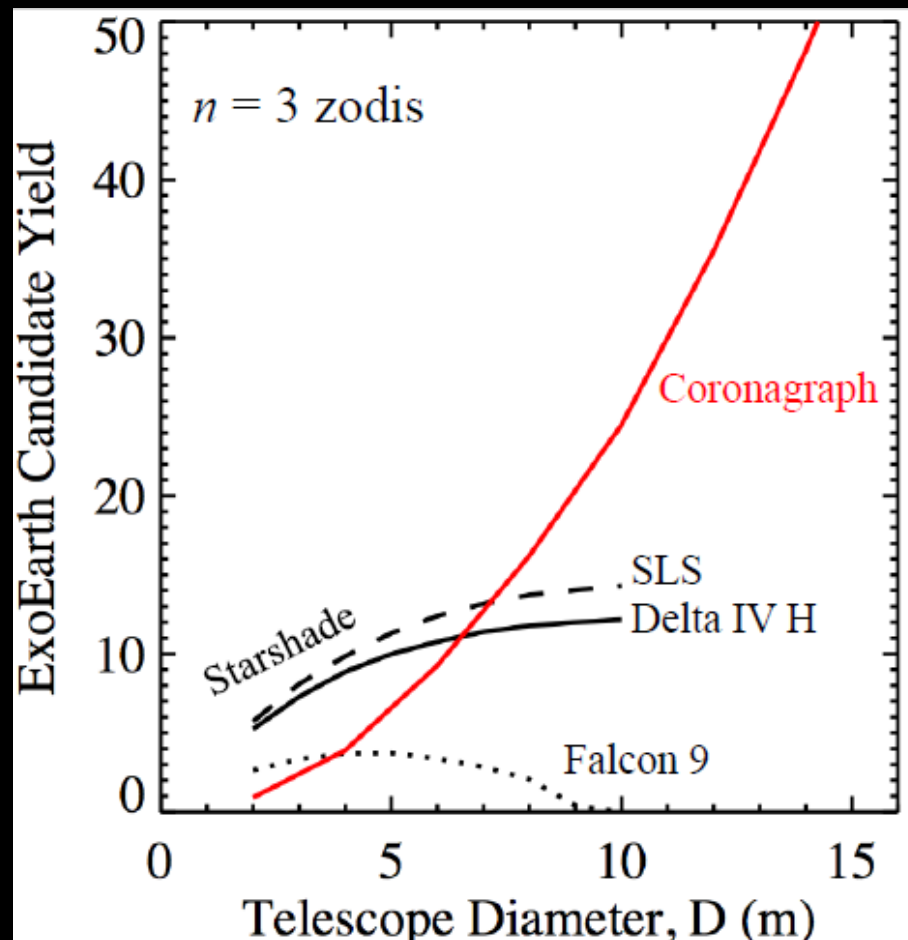


# Starshade Optical Shield



# Starshade and Coronagraph as a Function of Telescope Diameter

- Starshades appear to provide greater yield for telescope apertures less than ~6 m (depending upon launch vehicle and exozodi)



Credit: C. Stark et al 2016

# Possible New Worlds Exoplanet Telescopes

(mid 2030s)

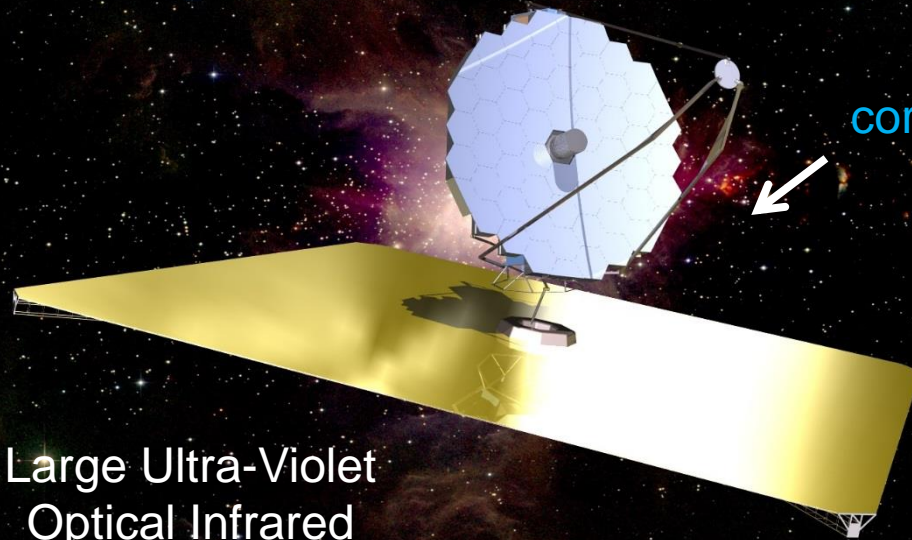
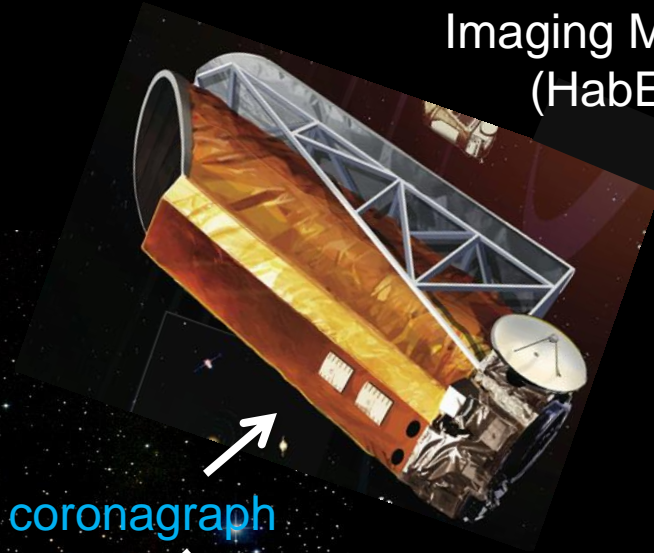
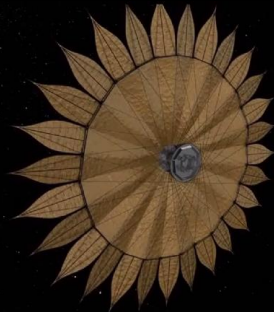
Habitable Exoplanet  
Imaging Mission  
(HabEx)

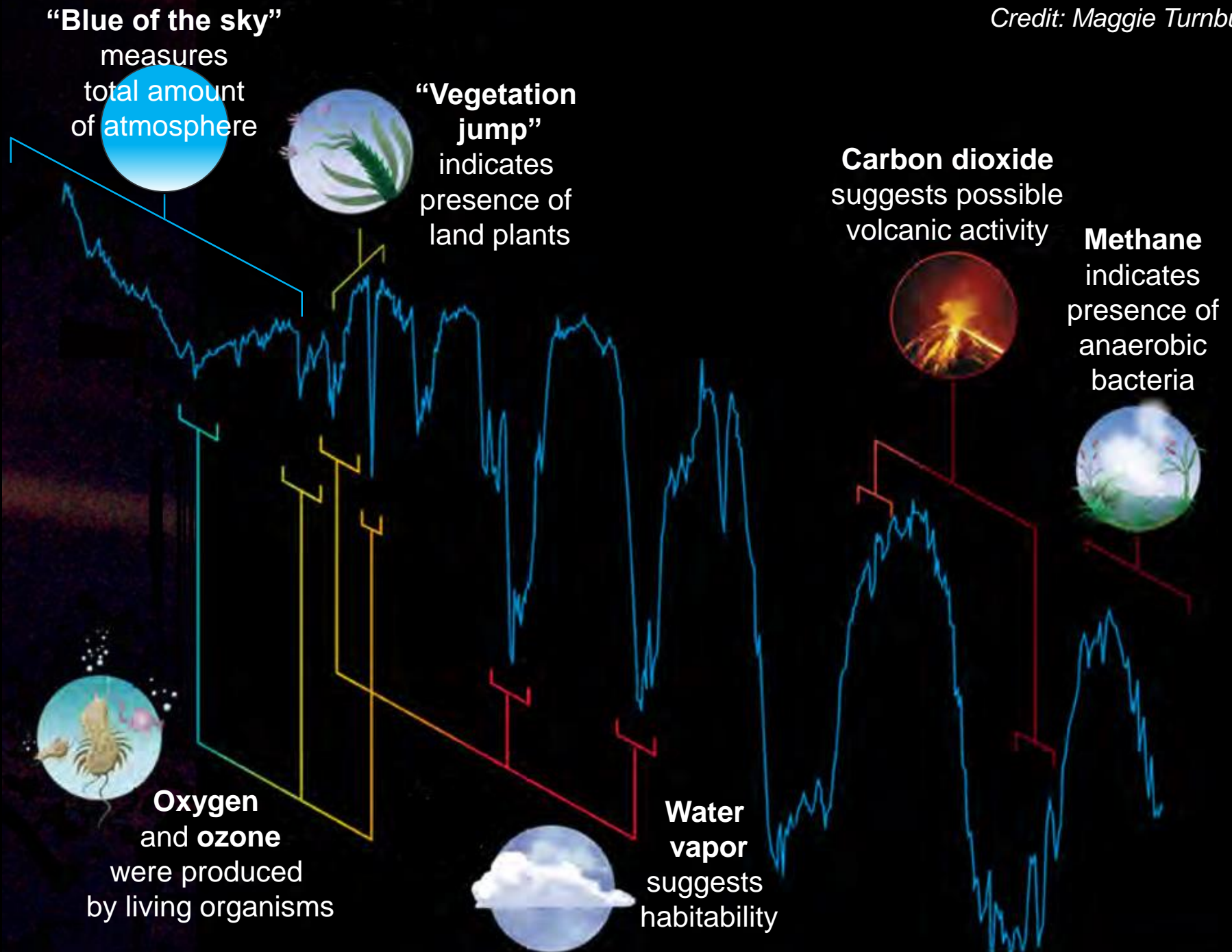
starshade

coronagraph

Large Ultra-Violet  
Optical Infrared  
Telescope (LUVOIR)

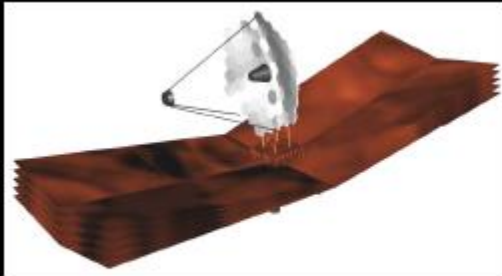
Origins Space  
Telescope (OST)



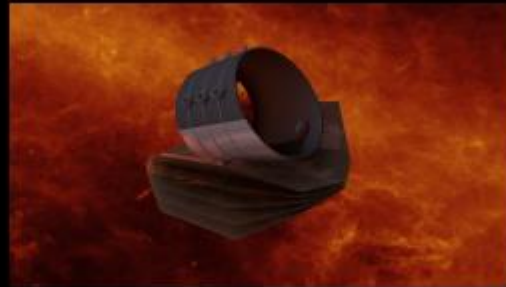


# Origins Space Telescope

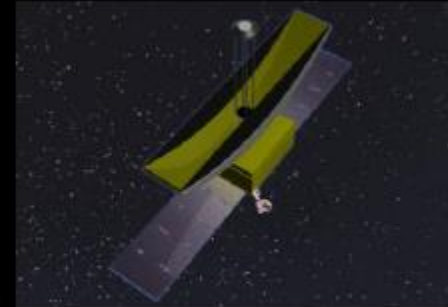
*Credit: A. Cooray*



JWST-like?



Spitzer-like?



Rotating aperture?

- 8–13 m single aperture
- 5–600  $\mu\text{m}$
- 4.5 K active-cooled
- Exoplanets
  - Transit/secondary eclipse spectroscopy
  - Direct imaging via a mid-IR coronagraph

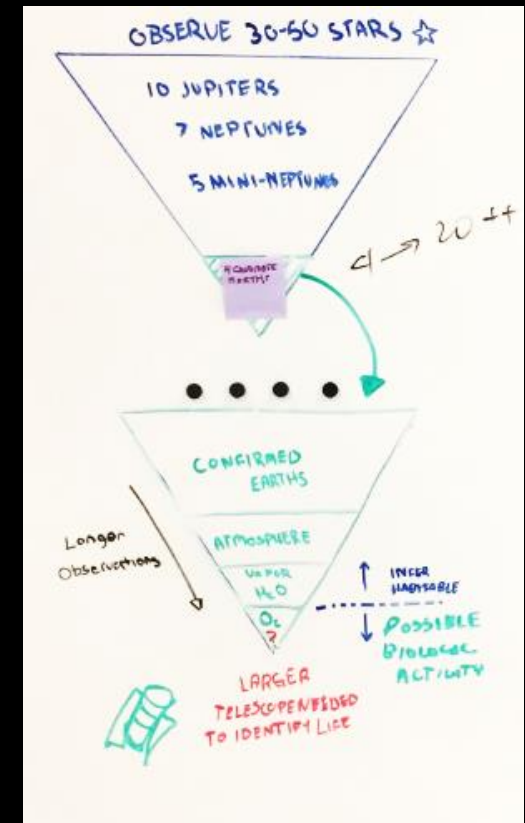
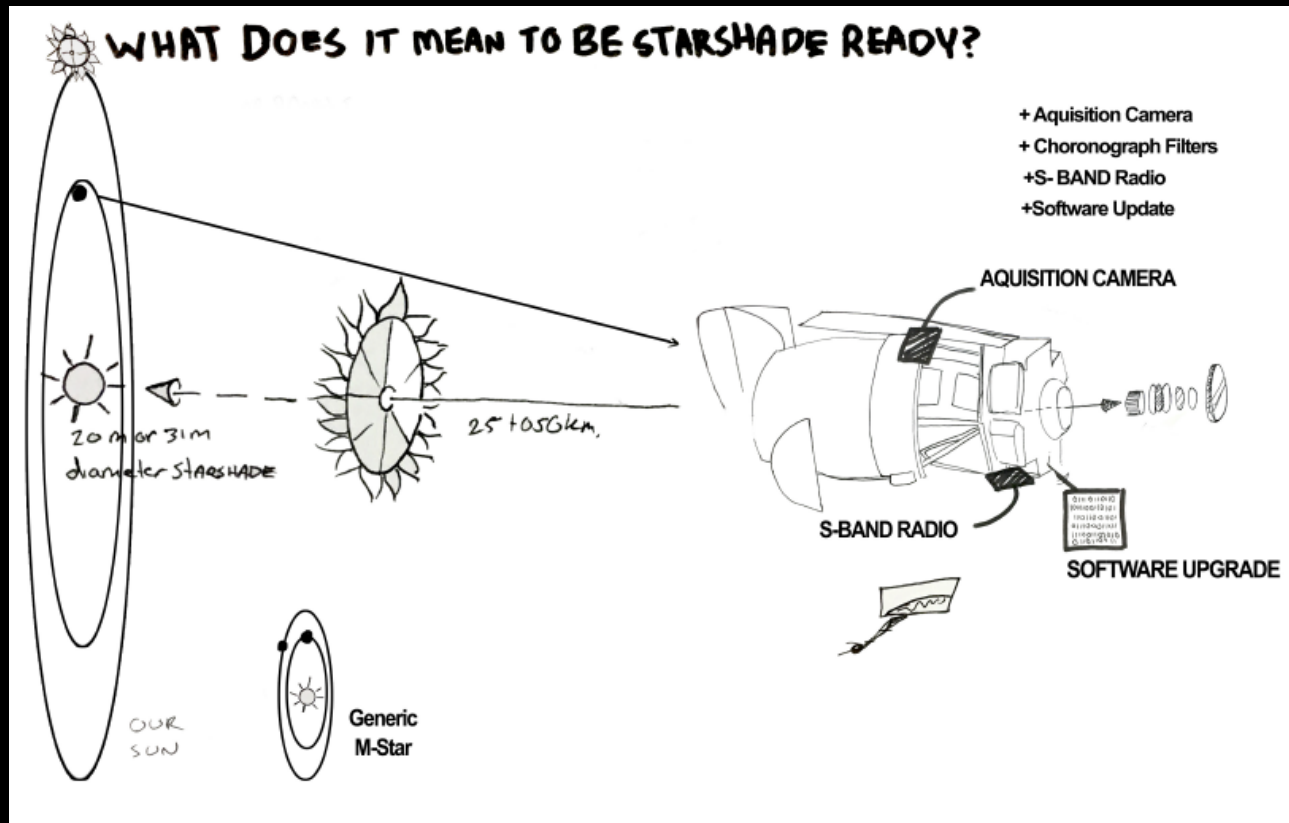
# Support for Decadal Large Mission Studies

- Charter signed for Exoplanet Standards and Definition Team
  - Completed ExoSIMS science planning and yield tool for large mission studies (Savransky, Morgan)
- Considered inputs from LUVOIR, HabEx, and OST in updated definition of Program Technology Gap list
- Made presentations to all four flagship study STDs
  - Keith Warfield (PCE) on lessons learned from prior decadal surveys
  - Gary Blackwood on architecture trade methods
- High Contrast Imaging technology initiatives
  - Segmented Coronagraph Design & Analysis: program-funded study to evaluate coronagraph designs suitable to segmented apertures. See Stuart Shaklan's recent online colloquium at [https://exoplanets.nasa.gov/exep/technology/tech\\_colloquium/](https://exoplanets.nasa.gov/exep/technology/tech_colloquium/)
  - Planning for experimental demonstration of  $10^{-10}$  raw broadband contrast in HCIT; goal of 2019 completion

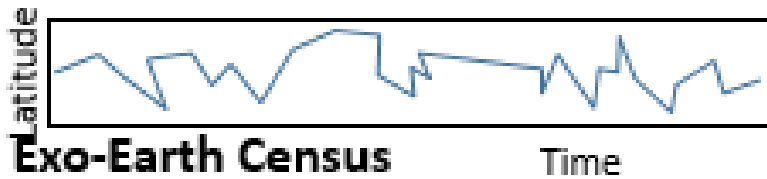
# WFIRST Starshade-Ready

Accommodation Study to Enable a Rendezvous at L2

- WFIRST Starshade can directly image habitable-zone exo-earths in late 2020s



# Two Possible Starshade Science Programs



- For 2 years, target as many nearby stars as possible
  - At each star, stay long enough to detect an Exo-Earth if present
  - In the third year, revisit to confirm and characterize
  - Create a list of possible Earth-like planets for a future mission like HABEX or LUVOIR
- Pick the nearest 10–12 solar-type stars
  - Observe each long enough to get spectra on any planets that might be present
  - Return to the most interesting systems to further characterize
  - Will see many planets, including an Exo-Earth or two

# Coronagraph/Telescope Technology Needs

## Contrast



Coronagraph architectures



Deformable mirrors

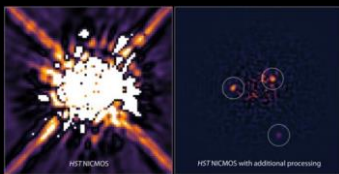
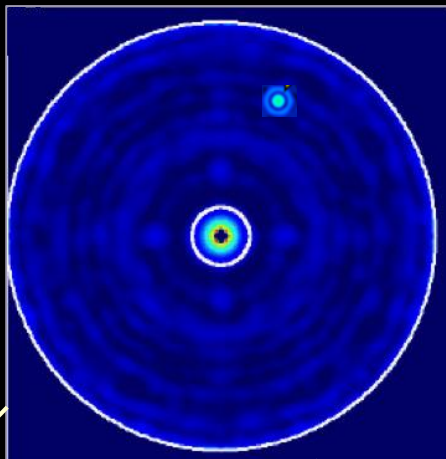
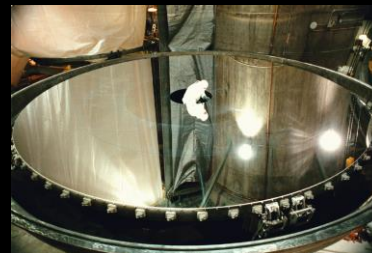


Image post-processing



## Angular Resolution

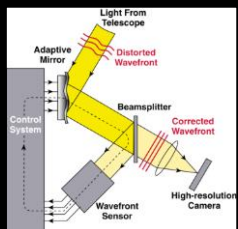


Large monolith



Segmented

## Contrast Stability



Wavefront sensing and control

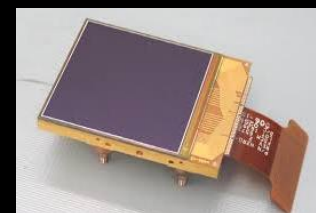
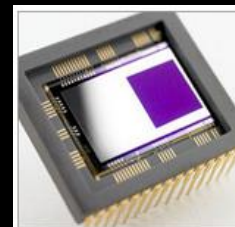


Segment phasing and rigid body sensing and control



Telescope vibration sensing and control

## Detection Sensitivity



Ultra-low noise visible and infrared detectors

# Starshade Technology Needs

## 1) Starlight Suppression



Suppressing scattered light off petal edges from off-axis Sunlight (S-2)



Suppressing diffracted light from on-axis starlight (S-1)

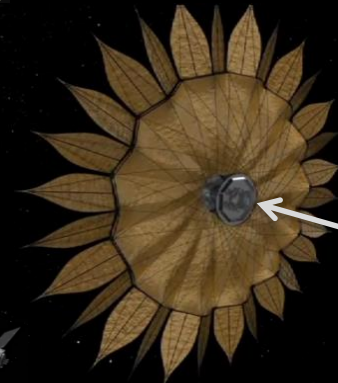


## 3) Deployment Accuracy and Shape Stability

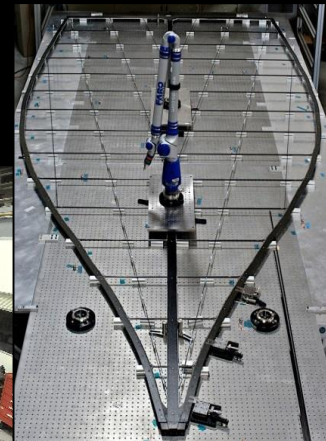


Positioning the petals to high accuracy, blocking on-axis starlight, maintaining overall shape on a highly stable structure (S-5)

## 2) Formation Sensing and Control



Maintaining lateral offset requirement between the spacecrafts (S-3)



Fabricating the petals to high accuracy (S-4)

# Starshade Technology Development Activity

## Starshade to TRL 5 (S5)

- Purpose: achieve TRL5 to support future exoplanet missions with significant progress for consideration by the 2020 Decadal Survey
- Currently developing a technology development plan as a recommendation to the Astrophysics Division in late 2017
- Held an all-day public Starshade Technology Workshop in Pasadena, CA on December 1, 2016
  - Broad institutional participation – over 80 local and remote participants from NASA, industry, and academia
  - Discussed the technology development needs and opportunities for future planning and prioritization
- Next steps: three follow-on workshops in late March–May for major technical themes and trades identified in the December workshop



Program Overview

Science Updates

How Do We Discover & Characterize Exoplanets?

Progress towards 2010 Decadal Survey Priorities

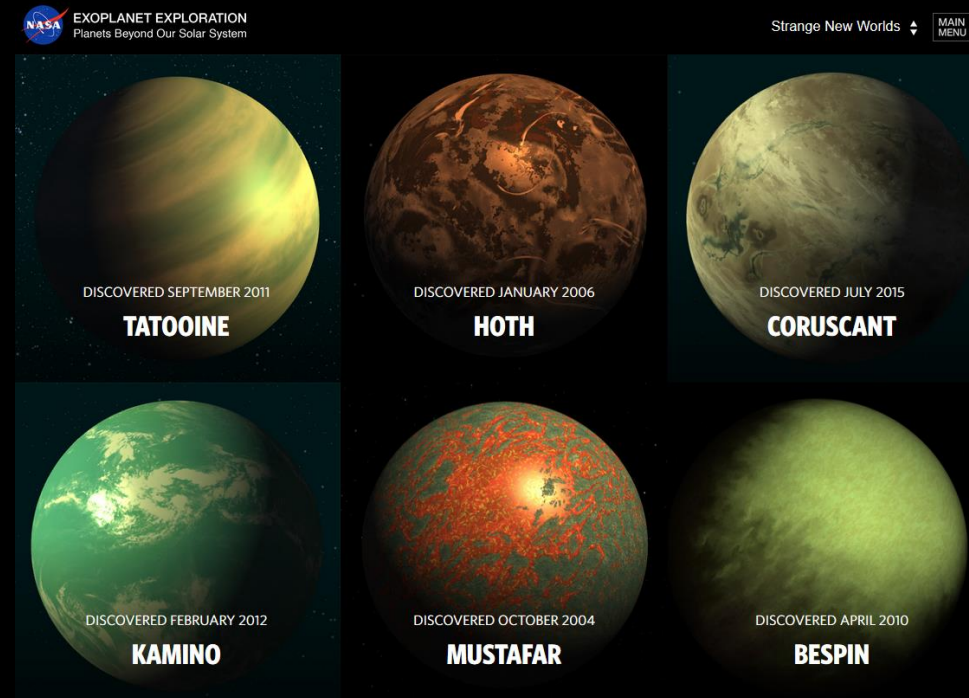
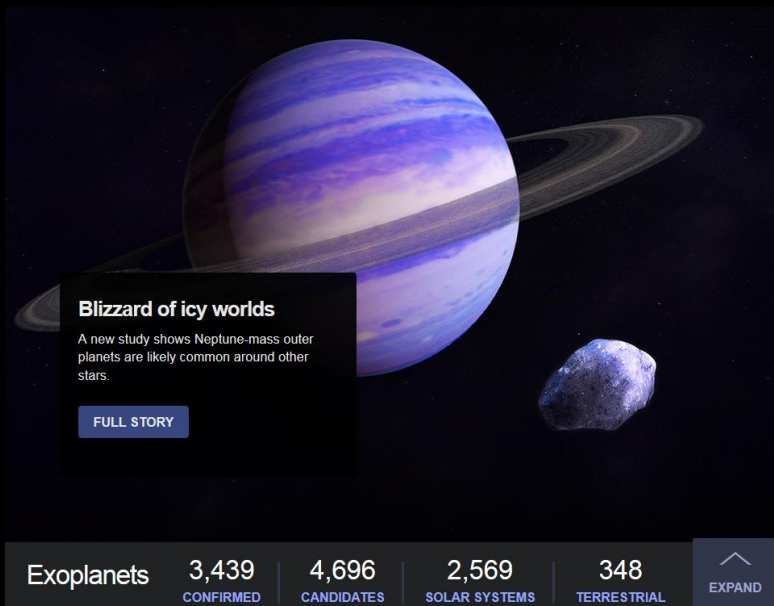
Plan Forward: Science and Technology

ExoComm: Show Me the Planets!

# Exoplanet Communications

Data Visualization Tools and New Thematic Exoplanet Hub

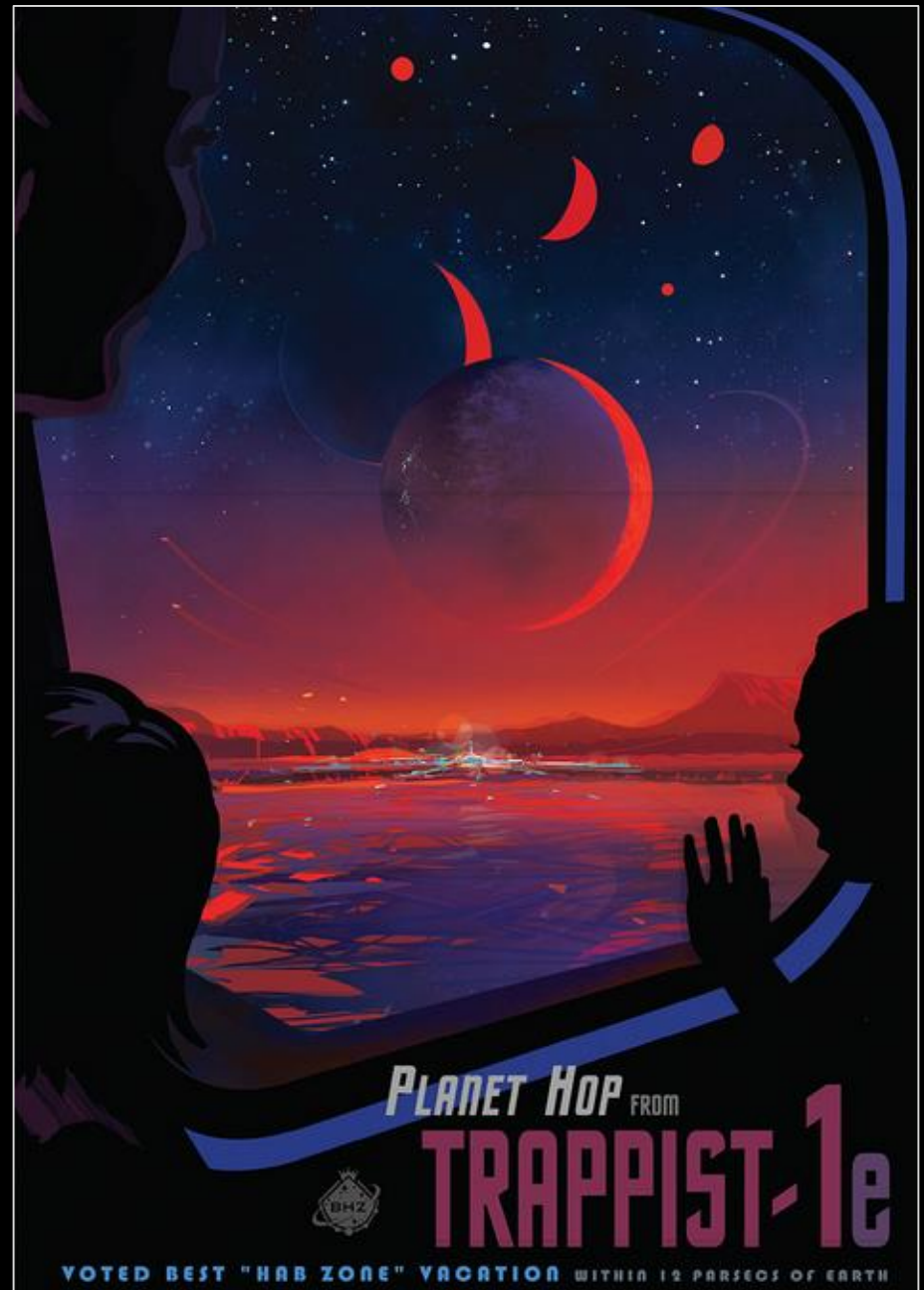
[exoplanets.nasa.gov](https://exoplanets.nasa.gov)



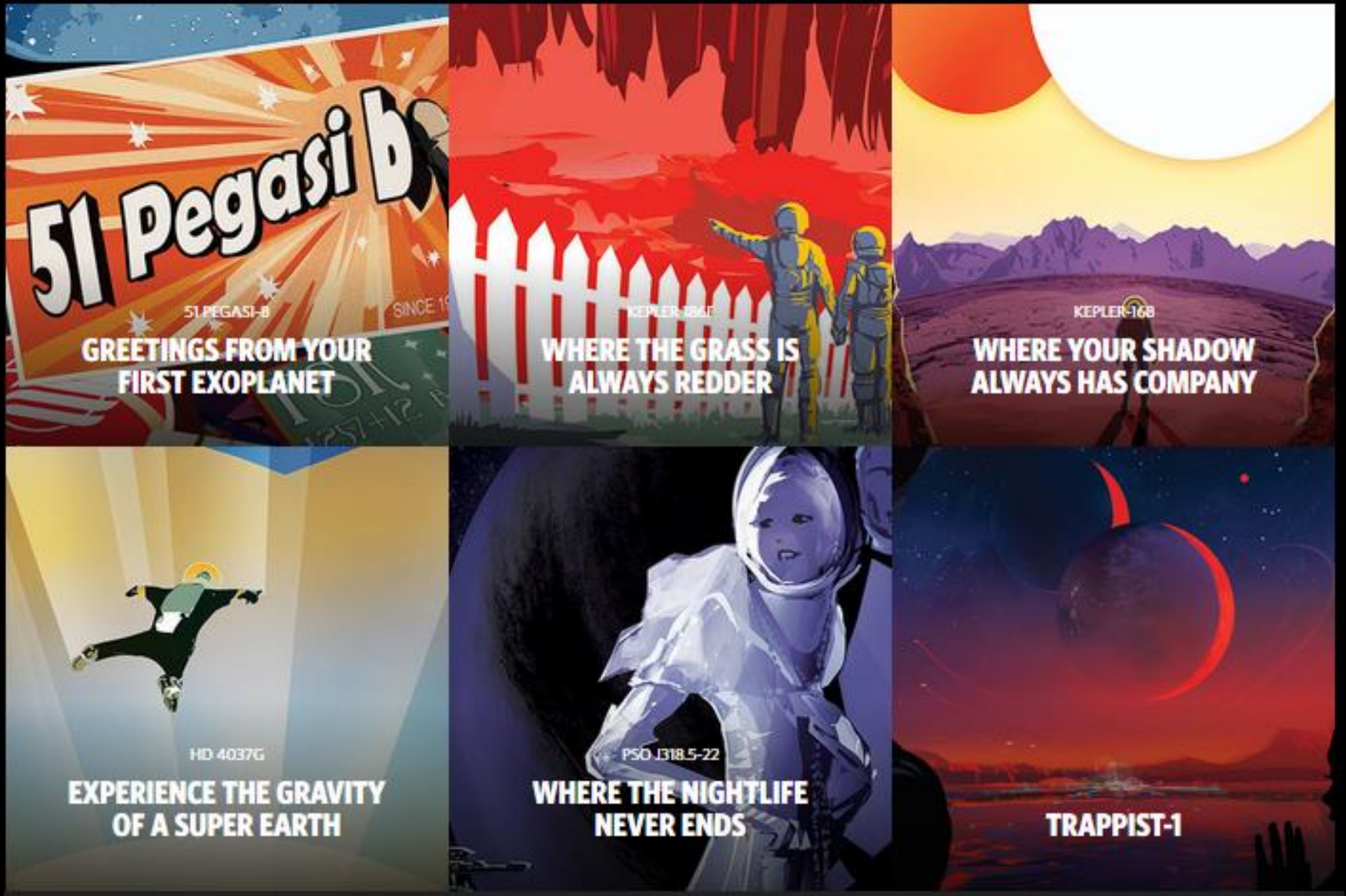
Replaced [exoplanets.jpl.nasa.gov](https://exoplanets.jpl.nasa.gov)  
Exoplanet-thematic content featuring  
content across NASA.

3D, interactive planet renderings  
Custom planet textures can be created  
for press releases.  
(contact the Comm team in advance)

# Exoplanet Travel Bureau



# Exoplanet Travel Bureau



# Exploring a Galaxy of Worlds while Inspiring Our Own



Introducing Baby Kepler! (Cloutier)

DOB 2/6/16 • Age on Earth – 1 • Kepler 16b – 1.5 • Proxima b – 33 • Trappist-1b – 243



**Jet Propulsion Laboratory**  
California Institute of Technology

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[jpl.nasa.gov](http://jpl.nasa.gov)



National Aeronautics and  
Space Administration

Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California

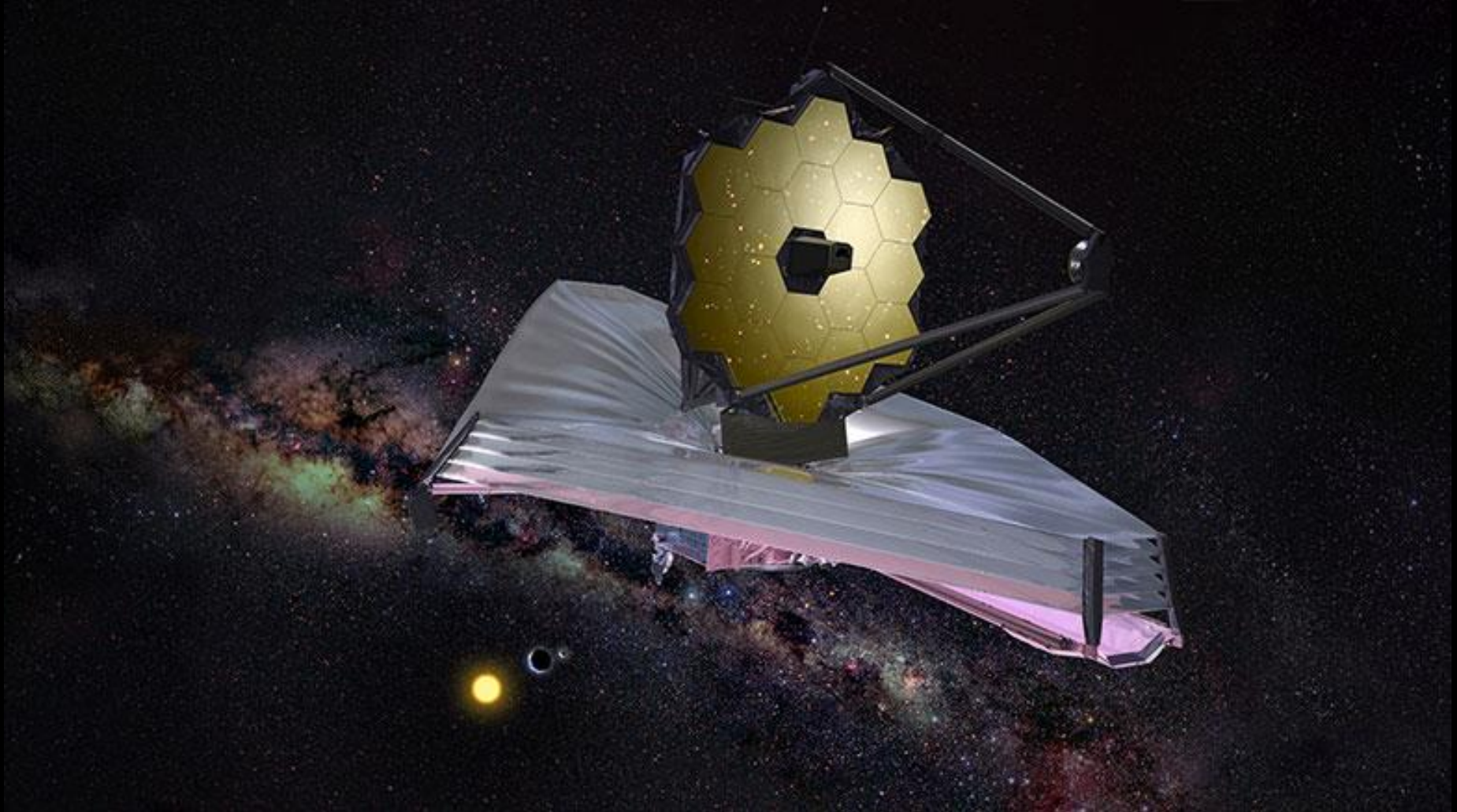
# Acknowledgements

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration. © 2017 All rights reserved.

- Work was also carried out at NASA's
  - Goddard Space Flight Center
  - Ames Research Center
- Work was carried out as well under contracts with the National Aeronautics and Space Administration and
  - Princeton University
  - University of Arizona
  - Northrop Grumman Aerospace Systems
  - National Optical Astronomy Observatory (NOAO)
  - Massachusetts Institute of Technology
  - Pennsylvania State University
- Contributions from ExEP program leadership and staff gratefully acknowledged

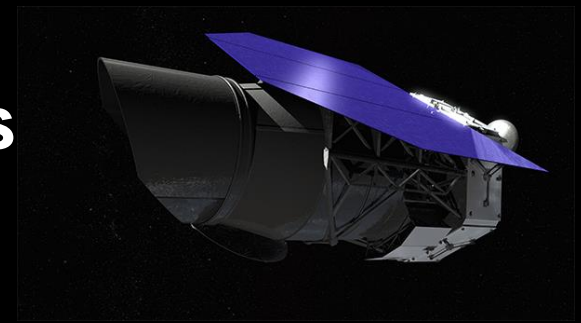
# James Webb Space Telescope

Launch 2018



*Credit: NASA, STSci*

# WFIRST Technology Milestones



- NIR Detector
  - **Milestone 4:** Completed. Full arrays demonstrate a yield of >20% (and meet derived requirements)
  - **Milestone 5:** Environmental tests of flight-like sensor chip assembly complete, report in preparation
- Coronagraph
  - **Milestone 7:** Completed. Spectrograph dark current <0.001 e/pix/s and read noise <1e-/pix/frame
  - **Milestone 8:** Not met. PIAACMC <10<sup>-8</sup> raw contrast 10% broadband in static environment
  - **Milestone 9:** Completed. OMC <10<sup>-8</sup> raw contrast at 10% broadband in dynamic environment.